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**THE U.S. RESPONSE TO NEOS: AVOIDING A BLACK
SWAN EVENT**

by

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September 2016

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THE U.S. RESPONSE TO NEOS: AVOIDING A BLACK SWAN EVENT

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Submitted in partial fulfillment of the
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ABSTRACT

Near Earth Objects (NEOs) present one of the greatest threats to Earth, but currently there is no U.S. or international response and mitigation strategy in place for a NEO impact. This thesis examines case studies from two other high impact low probability (HILP) events—earthquakes and volcanoes—with the intent of applying lessons learned to the formulation of a NEO mitigation strategy. The case studies include domestic and international examples, offering insights into the critical areas of education and training, infrastructure, and communications. Considering the destructiveness of the threat, it would be in the best interests of global leaders to develop a NEO strategy that uses best response practices from these other events. This thesis recommends the use of an early warning system, greater involvement of leadership, and crowdsourcing ideas beyond the public sector.

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LIST OF ACRONYMS AND ABBREVIATIONS

ARM	Asteroid Redirect Mission
ASE	Association of Space Explorers
BAO	Beijing Astronomical Observatory
CCD	Charge Coupled Device
COBRA	Cabinet Office Briefing Room
COPUOUS	Commission on the Peaceful Uses of Outer Space
DEM	Department of Emergency Management
EOC	Emergency Operations Center
ESA	European Space Agency
EU	European Union
FEMA	Federal Emergency Management Agency
HILP	high impact low probability
IAA	International Academy of Astronautics
IAVW	International Airways Volcano Watch
IAWN	International Asteroid Warning Network
ICAO	International Civil Aviation Organization
IMO	Icelandic Meteorological Office
IVATF	International Volcanic Ash Task Force
JPL	Jet Propulsion Lab
KM	kilometer
KT	Cretaceous-Tertiary
MPC	Minor Planet Center
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NEOO	Near Earth Object Observations Program
NSF	National Science Foundation
NVEWS	National Volcano Early Warning System
OHDACA	Overseas Humanitarian Disaster and Civic Aid
OIG	Office of Inspector General
PDCO	Planetary Defense Coordination Office

PHA	Potentially Hazardous Asteroid
PHO	Potentially Hazardous Object
PIERWG	Planetary Impact Emergency Response Working Group
SCAP	Schmidt CCD Asteroid Program
SIGMET	Significant Meteorological
SMPAG	Space Mission Planning Advisory Group
SSA	Space Situational Awareness
TNT	trinitrotoluene
UASI	Urban Areas Security Initiative
UN	United Nations
USAF	United States Air Force
USAID	United States Agency for International Development
USGS	United States Geological Survey
VAAC	Volcanic Ash Advisory Center

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I. INTRODUCTION

A. MAJOR RESEARCH QUESTION

There was a time when people believed that all swans were white, and the mythic black swan was the stuff of fairytales. Then came the discovery of Australia, and the black swans that are native to that continent. In 2001, Nassim Nicholas Taleb advanced the three principles of his “black swan theory”: 1) the event is a rarity, 2) the impact is extreme, and 3) the event can be explained in retrospect.¹ To Taleb, the black swan symbolizes that there is “a severe limitation to our learning from observations or experience” and a “fragility of our knowledge.”²

A Near Earth Object (NEO) impact falls into the category of a black swan or high impact low probability (HILP) event as it meets each of the three aforementioned criteria. NASA defines NEOs as “comets and asteroids that have been nudged by the gravitational attraction of nearby planets into orbits that allow them to enter the Earth’s neighborhood.”³ To date, 14,166 NEOs have been discovered, of which 879 are asteroids that measure 1 km or greater in diameter.⁴ In addition, 1,689 NEOs are considered Potentially Hazardous Asteroids (PHAs).⁵ While the topic of NEOs is not necessarily new—and even though NEOs present a grave existential threat to the United States and the international community—because impact is seen as a very low probability event, relatively little research has been done to examine possible mitigation strategies. It is only within the last two decades that any concerted national or international actions have been taken to examine potential responses to this threat. This thesis will examine if lessons from other HILP events could be applied to the NEO issue and possibly help form a more cohesive response strategy for the United States and other nations.

¹ Nassim Nicholas Taleb, “The Black Swan: The Impact of the Highly Improbable,” *The New York Times*, April 22, 2007, http://www.nytimes.com/2007/04/22/books/chapters/0422-1st-tale.html?_r=1.

² Ibid.

³ “Near Earth Object Program: Frequently Asked Questions (FAQ),” National Aeronautics and Space Administration (NASA), accessed September 4, 2016, <http://neo.jpl.nasa.gov/faq/>.

⁴ Ibid.

⁵ Ibid.

B. SIGNIFICANCE OF THE RESEARCH QUESTION

The topic of NEOs is particularly significant for a number of reasons, ranging from the catastrophic effects an impact would have on the United States and the world to the fact that Congress has tasked NASA to categorize 90 percent of all NEOs that are 140 meters or greater in diameter by 2020.⁶ The latter is a task that requires technological resources and cooperation from the international community.

In addition, some of the existing mitigation scenarios promote the use of nuclear weapons for a deflection campaign in space. The use of nuclear weapons in space is expressly forbidden, and such an action would violate the terms of the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, also known as the Outer Space Treaty. The Outer Space treaty explicitly states that, “States shall not place nuclear weapons or other weapons of mass destruction in orbit or on celestial bodies or station them in outer space in any other manner.”⁷ It would also violate the 1963 Limited Test Ban Treaty, which “prohibits nuclear weapons tests ‘or any other nuclear explosion’ in the atmosphere” and “in outer space.”⁸

Lastly, despite the potential catastrophic consequences of a NEO impact on Earth, there are no established disaster management protocols for U.S. emergency personnel to follow in the event of impact. Steps need to be taken to ensure that the threat of a NEO can be addressed in a manner that will minimize the fallout.

⁶ Russell Schweickart et al., “Asteroid Threats: A Call for Global Response,” Association of Space Explorers, September 25, 2008, 12, <http://www.space-explorers.org/ATACGR.pdf>.

⁷ “Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies,” United Nations Office for Outer Space Affairs, accessed April 4, 2016, <http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html>.

⁸ “Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and under Water,” United States Department of State, accessed May 11, 2016, <http://www.state.gov/t/isn/4797.htm>.

C. LITERATURE REVIEW

Researchers claim that an asteroid impacted Earth over 65 million years ago, causing the death of more than 70 percent of life on the planet.⁹ This theory is known as the Alvarez hypothesis and has been largely validated by the scientific community.¹⁰ The asteroid that caused the extinction of so many species is known as K-T and is estimated to have been 10 km in diameter. The Earth has not since experienced another natural event this catastrophic, but researchers are now looking closely at the threat of NEOs. As tracking and detection capabilities improve, even more potentially dangerous NEOs will likely be discovered.¹¹

The issue of NEOs is complex for a number of reasons, ranging from the arduous task of cataloging them to the development of national and global protocols for dealing with them. According to Chapman and Morrison, the cataloging “degree of completeness for 1 km objects is less than 5 percent.”¹² This fact is jarring, considering that NEOs in the range of 0.5 km can upset the ecosystem enough to impact crop production and “kill unprecedented numbers of people.”¹³ Although an impact may be geographically localized, the interconnectedness of today’s world means that the after-effects could be far-reaching. The situation is aptly described by researchers Lee, Preston, and Green, who state, “The impact of future crises are unlikely to remain local—regardless of their origins—and will likely affect more than one country or region. The vulnerabilities of globalized supply chains and particularly the just in time business model are likely to be exposed by any disruption lasting more than a few days.”¹⁴

⁹ “Dinosaurs – Why Did They Go Extinct?” Smithsonian National Museum of Natural History,” accessed April 4, 2016, http://paleobiology.si.edu/dinosaurs/info/everything/why_7.html.

¹⁰ Clark R. Chapman and David Morrison, “Impacts on the Earth by Asteroids and Comets: Assessing the Hazard,” *Nature* 367 (January 1994): 33, doi: 10.1038/367033a0.

¹¹ “Recommendations of the Action Team on Near-Earth Objects for an International Response to the Near-Earth Object Impact Threat,” United Nations Office for Outer Space Affairs, 6, accessed April 4, 2016, http://www.unoosa.org/oosa/oosadoc/data/documents/2013/aac.105c.11/aac.105c.11.329_0.html.

¹² Chapman and Morrison, “Impacts on the Earth by Asteroids and Comets,” 34.

¹³ Ibid., 33.

¹⁴ Bernice Lee, Felix Preston, and Gemma Green, *Preparing for High-Impact, Low-Probability Events: Lessons from Eyjafjallajokull* (London, United Kingdom: Chatham House, 2012), viii, accessed April 5, 2016, <https://www.chathamhouse.org/publications/papers/view/181179>.

The existing literature on NEOs focuses mainly on the importance of cataloging and characterizing NEOs, promoting international coordination and cooperation for NEO surveillance and deflection strategies, and theorizing mitigation strategies. Limited funding has created an obstacle to the comprehensive monitoring of NEOs. In addition, researchers largely cite international cooperation as necessary when addressing the NEO issue, but the question of who should participate, and to what degree, is more difficult to address. Lastly, as mentioned previously, the most popular proposed mitigation scenarios involve measures that could violate international treaties. Consequently, this literature review will discuss the current status of the NEO issue with the intent of identifying gaps in mitigation strategies, particularly those related to U.S. homeland security.

1. Catalog and Characterize NEOs

In 2001, the United Nations assembled an action team on NEOs with the purpose of coming up with recommendations for an international response to a NEO impact threat. The team proposed that the first step would be to identify the objects and assess the risk of impact to Earth.¹⁵ In addition, NASA is also working to meet U.S. congressional demands that call for the discovery and tracking of NEOs larger than 140 meters, which need to be at 90 percent completion by 2020.¹⁶ Funding is one of the major obstacles to meeting this goal.¹⁷ The International Asteroid Warning Network (IAWN) serves as the main hub for the institutions that monitor NEOs and acts as an “internationally recognized clearinghouse for the receipt, acknowledgment, and processing of all NEO observations.”¹⁸ IAWN has little online presence and few updates reflective of its small budget. This lack of resources would likely inhibit IAWN’s ability to coordinate with participating nations. A network would be better equipped to track and

¹⁵ “Recommendations of the Action Team on Near-Earth Objects,” United Nations Office for Outer Space Affairs, 1.

¹⁶ Russell L. Schweickart, “Decision Program on Asteroid Threat Mitigation,” *Acta Astronautica* 65, no. 9 (2009): 1403, doi: 10.1016/j.actaastro.2009.03.069.

¹⁷ Casey Johnston, “NASA Asteroid-tracking Program Stalled Due to Lack of Funds,” *Ars Technica*, August 13, 2009, <http://arstechnica.com/science/2009/08/nasa-asteroid-tracking-program-stalled-due-to-lack-of-funds/>.

¹⁸ “Recommendations of the Action Team on Near-Earth Objects,” United Nations Office for Outer Space Affairs, 2–3.

characterize NEOs more effectively than this single institution. Furthermore, the lack of investment signals a weakness for meeting the NEO tracking goal mandated by Congress.

2. International Cooperation and Coordination

Researchers agree that international coordination and cooperation is integral when dealing with the NEO issue, but the scope of these efforts is in question. In 2008, the Association of Space Explorers (ASE) set forth a report to the United Nations that called for the development of a global response protocol for planetary defense against a NEO impact.¹⁹ Despite this effort, the issue of international cooperation is multi-faceted and raises a number of questions. For example, the United States has taken the lead in NEO research, but a NEO could impact any part of the globe, which would necessitate participation from other nations. Former Apollo astronaut Russell Schweickart notes, “The need for international coordination in making such a decision is determined by the natural uncertainty regarding which specific populations are at risk in predicting an impact and the inherent shifting of risk in the process of deflection.”²⁰ A. C. Charania proposes that nations would likely have to pool technological resources for deflection missions in the event of a NEO impact,²¹ which would be difficult to execute due to limited manpower and funding.²² Additionally, there exists the problem of ascertaining whether only states with space capabilities and developed programs can participate in deflection mission planning. One proposed solution is to have space-faring states lead response efforts for “planetary defense.”²³ Unifying international allies in NEO research could increase monitoring capabilities, funding, and technology.

In addition, some proposed mitigation scenarios could lead to geopolitical issues for the United States. Researchers note that a deflection scenario that involves changing a

¹⁹ A. C. Charania and Agnieszka Lukaszczuk, “Assessment of Recent NEO Response Strategies for the United Nations,” *AIP Conference Proceedings* 1103, no. 393 (February 2009): 2, accessed April 5, 2016, <http://swfound.org/media/10045/neoresponse-al-iac-2009.pdf>.

²⁰ Schweickart, “Decision Program on Asteroid Threat Mitigation,” 1403.

²¹ Charania and Lukaszczuk, “Assessment of Recent NEO Response Strategies,” 3.

²² Ibid., 4.

²³ Ibid.

NEO impact site could compromise other areas if the process were “terminated or only partially completed.”²⁴ This scenario of a failed deflection attempt that would place the impact at another point along the “risk corridor” presents a major problem both for the inhabitants of the impact area and for the United States in terms of disrupting international relations, particularly with allies.²⁵ Schweickart argues that “a collaborative, global response is required...and it is highly desirable that a decision process, with agreed criteria, policies, and procedures be established prior to the development of a specific threat in order to assure that minimization of risk to life and property prevail over competing national self-interests.”²⁶ Due to uncertainty regarding impact point calculations, it can be difficult to know what states are at risk, thereby making the argument that a more comprehensive international participant buy-in is necessary.²⁷

3. Mitigation Strategies

A NEO impact would qualify as a natural disaster although an impact actually could be prevented, unlike other cases such as tsunamis and volcanoes for which no deflection scenario is feasible.²⁸ The U.N. Action Team on NEOs argues that this unique aspect “obligates the international community to establish a coordinated response to the NEO threat.”²⁹ Spacefaring states could have an opportunity to respond to a NEO event due to the potential for predictability and intervention. These mitigation strategies fall into the categories of space-based and Earth-based responses.

Space-based deflection responses are the most prominent category of mitigation models. According to Nicolas Peter, these responses range from: a) kinetic deflection where “a large spacecraft is sent to impact and deflect the NEO using only kinetic energy”; b) nuclear deflection where “nuclear explosions are triggered at a distance, on

²⁴ Schweickart, “Decision Program on Asteroid Threat Mitigation,” 1406.

²⁵ D. K. Yeomans et al., “Deflecting a Hazardous Near-Earth Object” (paper presented at the 1st IAA Planetary Defense Conference - Protecting Earth from Asteroids, Granada, Spain, April 27–30, 2009).

²⁶ Schweickart, “Decision Program on Asteroid Threat Mitigation,” 1403.

²⁷ Ibid.

²⁸ “Recommendations of the Action Team on Near-Earth Objects,” United Nations Office for Outer Space Affairs, 5.

²⁹ Ibid.

the surface or after penetration, provoking the ejection of rocks from the NEO, which in turn reacts by a small deflection”; c) nuclear destruction or “pulverization”; d) or a “billiards shot” where a small asteroid is purposely directed for collision with the threatening NEO.”³⁰ The 4th IAA Planetary Defense Conference held in April 2015 produced a paper stating that given the advanced lead time of a PHA, “impactors are the preferred deflection option for the more common, smaller asteroids.”³¹ Conversely, for asteroids that are larger and could result in “catastrophic” impact, or those that offer less response time, deflection via nuclear explosives may be the best option.³² In 2008, a Natural Impact Event Interagency Planning Exercise, involving subject matter experts from U.S. government entities, ran an exercise to simulate how the U.S. government might respond to a NEO impact. The exercise involved two scenarios: the first focused on a response to an impact predicted within 72 hours, and the second focused on deflection plans if the impact time was approximately seven years away. One of the major findings of this exercise was that the “NEO impact scenario is not captured in existing plans.”³³ In addition, conflicting views exist on which organization would take the lead in a deflection effort.³⁴

Moreover, space-based mitigation responses can be problematic due to legal and communications issues. The nuclear mitigation option would require revision of existing international laws and treaties.³⁵ Specifically, as noted earlier, placing nuclear weapons in space violates the 1967 Outer Space Treaty and the Test Ban Treaty of 1963.

³⁰ Nicolas Peter et al., “Charting Response Options for Threatening Near-Earth Objects,” *Acta Astronautica* 55 (August 2004): 328, doi: 10.1016/j.actaastro.2004.05.031.

³¹ David S. P. Dearborn and Jim M. Ferguson, “When an Impactor Is Not Enough: The Realistic Nuclear Option for Standoff Deflection” (paper presented at the 4th IAA Planetary Defense Conference - PDC 2015, Rome, Italy, April 13–17, 2015) 1.

³² Dearborn and Ferguson, “When an Impactor is Not Enough, 1.”

³³ Directorate of Strategic Planning, United States Air Force, *AF/A8XC Natural Impact Hazard (Asteroid Strike) Interagency Deliberate Planning Exercise After Action Report* (Washington, DC: United States Air Force Headquarters, December 2008), http://neo.jpl.nasa.gov/neo/Natural_Impact_After_Action_Report.pdf.

³⁴ Ibid.

³⁵ Peter et al., “Charting Response Options,” 329.

Considering the potential for lengthy debate on new legal precedents, it is not surprising that little work has been done to date.

Earth-based mitigation responses are limited to relocation and sheltering of those in the path of a NEO. The existing literature has made little mention of Earth-based scenarios, other than that the involvement of disaster management responders would be necessary if a NEO impact is not deflected. According to researchers Peter, Barton, Robinson, and Salotti, current communications among “relevant agencies” regarding strategies for NEO response missions are disorganized and badly executed.³⁶ This is alarming considering that experts estimate that due to the large number of uncategorized NEOs, a sudden unpredicted impact is more probable than a scenario in which a threatening NEO is discovered in time for mitigation strategies to be deployed.³⁷ This assertion is even more worrisome when coupled with the estimate by experts that Earth has a 1/3000 chance of being struck by a NEO measuring 1 km within the next century.³⁸

This review suggests that protocols for a NEO response need to be created, as do practices among emergency personnel. The existing body of literature on NEOs makes some mention of lessons from other HILP events, and how they could be useful in forming an effective mitigation and communications strategy. However, no in-depth study relating the two has been developed.

D. POTENTIAL EXPLANATIONS AND HYPOTHESES

Although the United States may be the leading nation in NEO research, it is still ill prepared to deal with the consequences of a NEO impact.³⁹ Avoiding and mitigating a NEO impact can only come to pass if there is, as Schweickart argues, a “capable early warning system, a deflection capability, and an institutional process capable of making timely decisions.”⁴⁰ Currently, none of the aforementioned tools are fully functioning.

³⁶ Peter et al., “Charting Response Options,” 326.

³⁷ Ibid.

³⁸ Chapman and Morrison, “Impacts on the Earth by Asteroids and Comets,” 39.

³⁹ Nicholas J. Bailey et al., “Global Vulnerability to Near-Earth Object Impact,” *Risk Management* 12, no. 1 (2010): 49, doi:10.1057/rm.2009.16.

⁴⁰ Schweickart, “Decision Program on Asteroid Threat Mitigation,” 1405.

Research has found that the mitigation process for NEOs is not broken, but rather that it is virtually non-existent and that “the management and design of NEO response missions and communication between the relevant agencies are poorly addressed.”⁴¹ As discussed in the literature review, some of the major obstacles are related to funding issues, poor communications, and technological boundaries.

This thesis will focus on the hypothesis that other HILP event response strategies could be applied to a NEO impact. Specifically, strategies that could be most applicable for a NEO response relate to: 1) education and training, 2) infrastructure development, and 3) communications strategy. Initial research for this thesis suggests that the United States could take active steps to inform disaster management organizations on the NEO threat. While an event such as K-T impact may pose insurmountable problems for an Earth-based disaster response because of its implications, a smaller NEO impact might be addressed by a coordinated national and international strategy.

E. RESEARCH DESIGN

This thesis will employ a case study approach to assess how the domestic and international communities prepare and respond to HILPs. These cases of other HILP will be analyzed in regard to their potential application to NEO impact mitigation strategies. Specifically, this thesis aims to draw parallels between such HILP events as volcano eruptions and tsunamis and to examine whether lessons learned from those events could be applied to an impending NEO impact threat response.

⁴¹ Peter et al., “Charting Response Options,” 326.

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II. BACKGROUND ON NEO EVENTS

To date, there have been three noteworthy NEO Earth impact events. The first occurred over 65 million year ago in the Gulf of Mexico, while the second impacted rural Russian territory known as Tunguska in 1908. The third, most recent impact happened in Chelyabinsk, Russia, in 2013. Despite the large threat posed by a NEO impact, no formal mitigation strategy exists. This chapter will present background information on past NEO events and outline the current state of NEO responses.

A. K/T IMPACT

A mass extinction event, known as K-T or Cretaceous-Tertiary, occurred 65 million years ago and according to researchers, wiped out approximately 70 percent of Earth's species including most of the dinosaurs.⁴² For decades, researchers were unable to find the root problem that caused the extinction until 1980 when physicist Luis Alvarez and his son, a geologist, found a large amount of iridium in the sedimentary layers from the Cretaceous period.⁴³ For reference, iridium is often found in asteroids but is a rarity to Earth. The Alvarez Theory hypothesizes that a 6-mile wide meteor, composed mostly of iridium, struck the Earth. The size of the meteor would account for the global layer of iridium in the sediment.⁴⁴ Moreover, the meteor impact would have caused incredibly high temperatures that led to massive fires, which is supported by the presence of soot found in the sediment layer near the iridium.⁴⁵ This hypothesis has become the leading theory for the mass extinction event and is largely validated by the scientific community. The Chicxulub crater, located in the Yucatan, corroborates the events outlined by the Alvarez theory as it is 112 miles in diameter and is estimated to be 65 million years old.⁴⁶

⁴² “K-T Event,” National Aeronautics and Space Administration (NASA), accessed September 4, 2016, <http://www2.jpl.nasa.gov/sl9/back3.html>; *Encyclopaedia Britannica*, s.v. “K-T Extinction,” last modified July 17, 2016, <https://www.britannica.com/science/K-T-extinction>.

⁴³ “K-T Event,” NASA.

⁴⁴ Ibid.

⁴⁵ Ibid.

⁴⁶ Ibid.

A number of other natural disasters—ranging from tsunamis, volcanic eruptions, and earthquakes, to massive fires—resulted from the impact that created the Chicxulub crater.⁴⁷ The K-T event was equivalent to the detonation of 100,000 billion tons of TNT, causing “an earthquake one thousand times greater than the largest ever recorded.”⁴⁸ K-T shot a substantial quantity of debris into and above the atmosphere, which led to long-lasting and destructive after-effects. Large fragments re-entered the atmosphere at velocities high enough to cause global forest fires on impact. The remaining fine dust particles settled in the atmosphere, effectively blocking sunlight and causing temperatures to drop, resulting in a phenomenon called “impact winter.”⁴⁹

B. THE TUNGUSKA IMPACT

Although not nearly as devastating as K-T, the Tunguska, Russia, impact in 1908 became the first large-scale asteroid event in modern history.⁵⁰ The impact caused the destruction of 2,000 square miles of surrounding forest, or approximately 80 million trees.⁵¹ Residents living as far as 40 miles away felt the heat from the impact.⁵² In addition, the meteor caused an earthquake that allowed seismic shockwaves to travel as far as England.⁵³ Asia reported lighter night skies, a result of light reflecting off of dense clouds and a chemical reaction.⁵⁴ Wildlife in the area was decimated, but as the region was sparsely populated, there were no human casualties.⁵⁵

Interestingly, despite the rural environment, the Tunguska event offered researchers the first eyewitness accounts of a NEO event. One such witness recounted

⁴⁷ “K-T Event,” NASA.

⁴⁸ “Dinosaurs – Why Did They Go Extinct?” Smithsonian.

⁴⁹ Ibid.

⁵⁰ “The Tunguska Impact - 100 Years Later,” NASA, accessed July 9, 2016, http://science.nasa.gov/science-news/science-at-nasa/2008/30jun_tunguska/.

⁵¹ Melissa Hogenboom, “In Siberia in 1908 a Huge Explosion Came out of Nowhere,” BBC, July 7, 2016, www.bbc.com/earth/story/20160706-in-siberia-in-1908-a-huge-explosion-came-out-of-nowhere.

⁵² Ibid.

⁵³ “The Tunguska Impact,” NASA.

⁵⁴ Christopher F. Chyba, Paul J. Thomas, and Kevin J. Zahnle, “The 1908 Tunguska Explosion: Atmospheric Disruption of a Stony Asteroid,” *Nature* 361 (January 1993), 43, doi: 10.1038/361040a0.

⁵⁵ Hogenboom, “In Siberia in 1908.”

that “the sky was split in two, and high above the forest the whole northern part of the sky appeared covered with fire...At that moment there was a bang in the sky and a mighty crash...The crash was followed by a noise like stones falling from the sky, or of guns firing.”⁵⁶ The firsthand accounts offer valuable insight into both a NEO impact and the aftereffects.

The impact at Tunguska was the equivalent of 185 Hiroshima atomic bombs, or 10–15 megatons of TNT.⁵⁷ Despite the sizable force and impact, no formal study was conducted until 1927 when Leonid Kulk and a Russian team ventured to the area.⁵⁸ The area exhibited a butterfly shape with the head portion as the “epicenter of the explosion” or “the point where the shock wave first” hit.⁵⁹ The team found no impact crater, which Kulk explained was likely due to the soggy terrain and the buried meteor material. Kulk hypothesized that a dig would produce evidence of the meteor at depths of approximately 25 meters. In 2013, Kulk’s hypothesis was confirmed by researchers who analyzed rock samples and found the “rocks had meteoric origin.”⁶⁰ To add further evidence to the theory, the samples were collected from a layer of peat that was carbon dated to 1908.⁶¹ Researchers now estimate that the asteroid weighed 220-million pounds and sped toward Earth at 33,500 miles per hour—factors that caused surrounding air to heat and reach 44,500 degrees Fahrenheit.⁶² This incredible heat caused the asteroid to consume itself, which also explains why there is no impact crater as the damage seen was due to the resulting shockwave.⁶³

⁵⁶ Hogenboom, “In Siberia in 1908.”

⁵⁷ Ibid.

⁵⁸ Ibid.

⁵⁹ N. S. Vasilyev, “The Tunguska Meteorite Problem Today,” *Planetary and Space Science* 46, no. 2–3 (1998): 130 accessed September 4, 2016, <http://cecelia.physics.indiana.edu/life/meteorite/tunguska.html>.

⁶⁰ Hogenboom, “In Siberia in 1908.”

⁶¹ Ibid.

⁶² “The Tunguska Impact,” NASA.

⁶³ Ibid.

C. THE CHELYABINSK IMPACT

In 2013, without any warning, an asteroid entered the atmosphere and exploded over Chelyabinsk, Russia. Despite the fact that this event occurred in a more technologically advanced age than K-T or Tunguska, the asteroid was undetected and took the world, and Russia in particular, by surprise. The entry explosion of the meteor was “stronger than a nuclear explosion” and was picked up by monitoring stations in Antarctica.⁶⁴ The meteor emanated a bright light that was seen by many citizens. Eyewitnesses reported a bright flash of light followed by a shock wave, which damaged buildings, shattered windows, and caused injuries to more than 1500 people.⁶⁵

A key difference between the Chelyabinsk event and the K-T and Tunguska NEO impacts is that it occurred in a densely human populated area. Two minutes elapsed from the time of the meteor entering the atmosphere to the shock wave that caused serious structural damage.⁶⁶ Shattered windows caused great concern as outside temperatures were below -20 degrees Celsius.⁶⁷ Obviously, these conditions negatively impacted the population, which had received no forewarning for the NEO.

The meteor entered the atmosphere at approximately 9 AM and originated from the same direction as the rising sun, which is the main reason for the lack of forewarning. Neither a ground nor a space telescope could have registered the NEO because of its path of approach as the sun interferes with visual identification and radar.⁶⁸ Either a new technology needs to be invented to monitor these NEOs, or better ground mitigation strategies should be in place. Ideally, both would be employed, but considering possible time and funding constraints associated with creating and testing new technology, a

⁶⁴ Elizabeth Howell, “Chelyabinsk Meteor: A Wake-up Call for Earth,” *Space.com*, August 2, 2016, <http://www.space.com/33623-chelyabinsk-meteor-wake-up-call-for-earth.html>.

⁶⁵ V. V. Emel’yanenko and B. M. Shustov, “Near-Earth Space Hazards and Their Detection,” *Physics-Uspekhi* 56, no. 8 (2013): 833, doi: 10.3367/UFNe.0183.201308g.0885.

⁶⁶ D. W. Dunham et al., “A Concept for Providing Warning of Earth Impacts by Small Asteroids,” *Solar System Research* 27, no. 4 (2013): 315.

⁶⁷ Ibid.

⁶⁸ Emel’yanenko and Shustov, “Near-Earth Space Hazards,” 835.

ground-based mitigation impact scenario is more feasible in the near future. Overall, the Chelyabinsk event highlights a large gap in NEO tracking.

D. NEO RESPONSE PRACTICES

The examples reviewed above demonstrate that the threat of a NEO event is very real and suggest that both the international and domestic communities create an organized mitigation strategy to address this issue. Currently, both domestic and international communities have taken steps to research NEOs in order to better understand the potential threat and theorize ways to divert a NEO if needed. However, most of the mitigation strategies are space-based deflection scenarios rather than an earth-based response if a NEO impact is unavoidable. Similarly, the international community has also focused on the discovery and categorization of NEOs, but little in the way of a mitigation strategy has been formed.

1. Domestic Response Practices

NEO research and tracking is still relatively new, and formal searches did not start until the 1970s.⁶⁹ Prior to that time, NEO identifications were only spontaneous discoveries and not the result of a concentrated effort.⁷⁰ Throughout the 1980s, individual small university programs with better technology continued to discover NEOs, but these were small-scale efforts. The Palomar Observatory, located in California, tracked NEOs using a photographic telescope until 1994 when new technologies made their method obsolete. Larger efforts to research NEOs began in the 2000s and rose to a government level.

In 1998, NASA representatives met with the House Committee on Science and agreed to head a project to find at least 90 percent of NEOs 1km and larger.⁷¹ That goal was met by 2010 on a small budget that averaged \$4 million per year. Then, in 2005, the

⁶⁹ Tom Gehrels, “NEO Search Programs - Past, Present, and Future,” Space Programs and Technologies Conference, SPACE Conferences and Exposition, 2, <http://dx.doi.org.libproxy.nps.edu/10.2514/6.1996-4382>.

⁷⁰ Ibid.

⁷¹ Lindley Johnson, “NEO Program 2015 for SBAG #12,” Near-Earth Object Program, January 6, 2015, http://www.lpi.usra.edu/sbag/meetings/jan2015/presentations/SBAG_NEO_Program_Johnson.pdf.

U.S. Congress tasked the NASA to “discover, track, catalog, and characterize 90%” of NEOs greater than 140 m in diameter.⁷² The Near Earth Object Program, which was created to assist NASA with “detecting, tracking, and cataloging NEOs,” received approximately \$4 million per year from 2002–2010.⁷³ In 2014, that budget increased to \$40 million per year due to increased concern from the scientific community. To date, this program has identified 14,510 NEOs, of which 1711 have been categorized as Potentially Hazardous Asteroids (PHAs).⁷⁴ These findings of NEOs are passed along to the Minor Planet Center (MPC), located at the Smithsonian Astrophysical Observatory, where a comprehensive database of NEOs is maintained.⁷⁵ The MPC is funded by NASA’s NEO Observations Program and acts as an international clearinghouse for NEO information.⁷⁶

In 2015, NASA and FEMA partnered to create the Planetary Impact Emergency Response Working Group (PIERWG) to address hazards associated with a potential NEO impact.⁷⁷ In the event of an impending NEO impact, NASA would notify FEMA, which would then disseminate warnings to “Federal, State, and Local authorities, and emergency response institutions.”⁷⁸ The PIERWG is in its nascent stage and has admitted that coordinating procedures and decision-making will be difficult due to sparse information on the threat.⁷⁹

In early 2016, NASA created the Planetary Defense Coordination Office (PDCO) in response to a 2014 report by the NASA Office of Inspector General (OIG), which

⁷² Russell Schweickart et al., “Asteroid Threats: A Call for Global Response,” Association of Space Explorers, September 25, 2008, 12, <http://www.space-explorers.org/ATACGR.pdf>.

⁷³ “Near Earth Object Program: FAQ,” NASA.

⁷⁴ Ibid.

⁷⁵ “Planetary Defense Frequently Asked Questions (FAQ),” NASA, accessed July 7, 2016, <https://www.nasa.gov/planetarydefense/faq>.

⁷⁶ Ibid.

⁷⁷ “Planetary Impact Emergency Response Working Group (PIERWG) Charter,” Planetary Impact Emergency Response Working Group, accessed September 4, 2016, http://www.nasa.gov/sites/default/files/atoms/files/signed_pierwg_charter_10212015.pdf.

⁷⁸ Ibid.

⁷⁹ Ibid.

called for a more “efficient, effective, and transparent” program.⁸⁰ In particular, the OIG called for the formalization of the NEO Program and the inclusion of a strategic plan.⁸¹ The PDCO oversees “early detection of potentially hazardous objects (PHOs), tracking and characterizing PHOs and issuing warnings about potential impacts, providing timely and accurate communications, and performing as a lead coordination node in U.S. government planning for response to an actual impact threat.”⁸² The PDCO works in conjunction with NASA’s Near Earth Object Observations (NEOO) Program, the National Science Foundation (NSF), the Jet Propulsion Lab (JPL), the Federal Emergency Management Agency (FEMA), and the United States Air Force (USAF).⁸³ These organizations place an emphasis on the importance of communications and coordination, which are both aspects of disaster response that will be examined in the following case study chapters.

More research has been done on space mitigation strategies than on Earth impact scenarios. A number of researchers agree that the most viable options for space deflection of a NEO are a kinetic impactor, a gravity tractor, or nuclear detonation.⁸⁴ The nuclear option, while deemed the “most effective,” is also the most problematic. As stated in the previous chapter, it violates the terms of the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, also known as the Outer Space Treaty, and the 1963 Limited Test Ban Treaty.⁸⁵ These restrictions bring attention to the fact that international coordination is necessary for forming a reasonable NEO mitigation plan.

⁸⁰ “Planetary Defense Coordination Office,” NASA, accessed September 4, 2016, <https://www.nasa.gov/planetarydefense/overview>.

⁸¹ Ibid.

⁸² Ibid.

⁸³ “Planetary Defense Coordination Office,” NASA.

⁸⁴ Lindley Johnson, “Planetary Defense Coordination Office,” NASA, May 20, 2016, <https://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/9.25C%20Lindley%20Johnson.pdf>.

⁸⁵ “Blast Deflection,” NEOShield-2, accessed July 7, 2016, <http://www.neoshield.net/mitigation-measures/blast-deflection/>.

2. International Response Practices

In 2001, a UN assembled team, known as the Commission on the Peaceful Uses of Outer Space (COPUOUS), was tasked to come up with recommendations for an international response to a NEO impact threat. The team proposed that the first step would be to identify the objects and assess the risk of impact to Earth.⁸⁶ The creation of IAWN and the Space Mission Planning Advisory Group (SMPAG) were the answer to that recommendation. IAWN’s mission is to “establish a worldwide effort to detect, track, and physically characterize NEOs, to determine those that are potential impact threats to Earth.”⁸⁷ Membership includes “scientific institutions, observatories, and other interested parties,” that then analyze the possibility of an impact event and its potential effects.⁸⁸ SMPAG’s mission is to organize an international response plan for a NEO threat and is overseen by the European Space Agency (ESA).⁸⁹

In Europe, ESA addresses space-related issues, including NEO research. ESA is composed of 22 member states, which allows the agency greater financial capabilities to tackle large-scale projects, including the NEO threat. Specifically, ESA’s Space Situational Awareness (SSA) program, which was created in 2009, leads NEO research efforts. The SSA mission is to “support Europe’s independent utilization of, and access to, space through the provision of timely and accurate information and data regarding the space environment, and particularly hazards to infrastructure in orbit and on the ground” including the hazards associated with a NEO impact event.⁹⁰

The ESA SSA NEO Program aims to monitor NEO trajectories, predict potential impacts, “assess consequences of any possible impact,” and create deflection plans and

⁸⁶ ‘Recommendations of the Action Team on Near-Earth Objects,’ United Nations Office for Outer Space Affairs, 1.

⁸⁷ Leonard David, “Dealing with Asteroid Threats: UN Completes First Planning Phase,” *Space*, March 6, 2015, <http://www.space.com/28755-dangerous-asteroids-united-nations-team.html>.

⁸⁸ Ibid.

⁸⁹ Ibid.

⁹⁰ “About SSA,” European Space Agency, accessed July 8, 2016, http://www.esa.int/Our_Activities/Operations/Space_Situational_Awareness/About_SSA.

impact warnings.⁹¹ Data are collected from a comprehensive network of European sources, including professional and amateur astronomers. This information is then forwarded to the U.S. MPC for cataloging. In addition, the SSA NEO Coordination Center processes the data in order to determine if there are any “high risk impact predictions.”⁹² In the event that a high-risk impact prediction is made, the ESA SSA reaches out to JPL for confirmation, prior to the issuance of warnings.⁹³ This coordination between entities is important as it leads to a more robust and accurate picture of the NEO threat. The theme of coordination will also be prevalent in the following case study chapters that examine disaster responses to other HILP events.

China, one of the leading space powers, has not coordinated with other space programs in addressing the NEO threat, and scant information on its program is available. China started its own asteroid program, the Beijing Schmidt CCD Asteroid Program (SCAP), in 1995.⁹⁴ For reference, the Schmidt CCD is a type of advanced telescope named after its creator.⁹⁵ This specialized NEO telescope at the Beijing Astronomical Observatory (BAO) assists in NEO tracking. SCAP discovers and tracks NEOs while also providing information to the MPC.⁹⁶ SCAP’s other objective is to calculate NEO impact probability.⁹⁷ Ultimately, China does not allow for as much transparency regarding its NEO research efforts as the United States.

E. CONCLUSION

Despite the alarming effects of the K-T, Tunguska, and Chelyabinsk impacts, little has been done to create a response strategy for the threat. The United States and the

⁹¹ “About SSA,” European Space Agency.

⁹² “Near Earth Objects - NEO Segment,” European Space Agency, accessed September 4, 2016, http://www.esa.int/Our_Activities/Operations/Space_Situational_Awareness/Near-Earth_Objects_-_NEO_Segment.

⁹³ Ibid.

⁹⁴ Yuehua Ma, Haibin Zhao, and Dazhi Yao, “NEO Search Telescope in China,” *Proceedings of the International Astronomical Union* 2, no. 236 (2006): 382, doi: 10.1017/s1743921307003468.

⁹⁵ Ibid.

⁹⁶ Ibid.

⁹⁷ Ibid.

international community have taken steps to address the NEO hazard, but these efforts fall short of creating a holistic NEO strategy that includes greater global participation. Furthermore, government officials do not give explicit details outlining agency roles in the event of a NEO impact. The following chapters will review other, more known threats and pull lessons from each that could be used to create a more honed NEO mitigation strategy.

III. LESSONS FROM VOLCANIC ERUPTIONS

Volcanic eruptions are difficult to predict and can pose a threat to people and infrastructure, much like a NEO impact. Since there have been many more volcanic eruptions than NEO events in recorded history, the application of some of the established volcano disaster management protocols could offer a foundation for a NEO event strategy. This chapter examines two volcano case studies, the 1980 eruption of Mount St. Helens and the 2010 eruption of Eyjafjallajökull in Iceland. Each case study will include a brief background section, followed by the mitigation strategies employed by officials that focus on education and training, infrastructure, and communications.

A. MOUNT ST. HELENS ERUPTION

Mount St. Helens, in Washington State, is known as one of the Cascade Arc Volcanoes, a series of volcanoes clustered along the Cascade Mountains starting in Northern California and extending to British Columbia.⁹⁸ When it erupted in 1980, it caused the deaths of 57 people, and became what one expert described as “one of the most studied volcanic eruptions in the twentieth century.”⁹⁹

In the months leading to the eruption on May 18, 1980, thousands of small earthquakes occurred at the base of Mount St. Helens.¹⁰⁰ Based on the seismic activity noted by the U.S. Geological Survey (USGS), the U.S. Forest Service took measures months before the eruption to identify the potential hazard and limit loss of life by closing off Mount St. Helens above the timberline.¹⁰¹ Unfortunately, the public did not heed the roadblocks and took the potential threat lightly. Ultimately, a magnitude

⁹⁸ “Why Study Cascade Volcanoes?” United States (U.S.) Geological Survey, accessed June 15, 2016, https://volcanoes.usgs.gov/observatories/cvo/cascade_volcanoes.html.

⁹⁹ “How Volcanoes Work,” San Diego State University (SDSU) Geology Department, accessed September 4, 2016, http://www.geology.sdsu.edu/how_volcanoes_work/StHelens.html.

¹⁰⁰ “Mt. St. Helens Eruption,” SDSU Geology Department, accessed June 15, 2016, http://www.geology.sdsu.edu/how_volcanoes_work/StHelens.html.

¹⁰¹ Thomas F. Saarinen, “Warning and Response to the Mount St. Helens Eruption,” United Nations Office for Disaster Risk Reduction, accessed September 4, 2016, <http://eird.org/esp/cdcapra/pdf/eng/doc13413/doc13413-contenido.pdf>.

5 earthquake shook the mountain in the early morning hours and caused a simultaneous landslide along the “volcano’s northern bulge.”¹⁰² In the immediate aftermath of the earthquake, the information on the threat was not presented to the public by the media or by government agencies in a way that emphasized the severe impact of a volcanic event. Even after a state of emergency was declared in April and the National Guard offered enforcement assistance, locals continued to disregard the warnings. Some locals even began selling maps of the logging roads in the area, which allowed tourists to avoid the roadblocks.¹⁰³ Even so, researchers estimated that the roadblocks saved as many as 100,000 lives.¹⁰⁴

The landslide became, according to the USGS, the “largest debris avalanche on Earth in recorded history,” expelling debris that could have filled “1 million Olympic swimming pools.”¹⁰⁵ It also caused the loss of the cryptodome, a blockage of accumulated viscous magma, from the inside of the volcano.¹⁰⁶ This action resulted in depressurization within the volcano and in a “lateral blast” that removed 1,000 ft. off the top of Mount St. Helens.

The loss of the cryptodome and lateral blast caused extensive damage to the surrounding area. A dense population of trees spread over 150,000 acres was felled.¹⁰⁷ The 520 million tons of volcanic ash that resulted from the eruption spread eastward and caused “complete darkness in Spokane, Washington, 400 kilometers (250 miles) from the volcano.”¹⁰⁸ Ash fell as far as central Montana and in the Great Plains of the Central

102 “How Volcanoes Work,” SDSU Geology Department.

103 Saarinen, “Warning and Response.”

104 Ibid.

105 “Glossary,” U.S. Geological Survey, accessed June 15, 2016,
<https://volcanoes.usgs.gov/vsc/glossary/>.

106 “Cryptodome,” U.S. Geological Survey, accessed September 4, 2016,
<https://volcanoes.usgs.gov/vsc/glossary/cryptodome.html>.

107 James Maynard, “Reliving the Mount St. Helens Eruption of 1980,” *Tech Times*, May 8, 2016,
<http://www.techtimes.com/articles/156871/20160508/reliving-the-mount-st-helens-eruption-of-1980.htm>.

108 Ibid.

United States, more than 900 miles away from the eruption site.¹⁰⁹ In three days, the Mount St. Helens ash cloud spread across the United States, and in 15 days, it had circled the Earth.¹¹⁰

The ash from a volcano can be particularly dangerous for a number of reasons. For example, it can bury roads, buildings, and houses. The ash cloud is comprised of rock fragments, minerals, and volcanic glass. It is “hard, abrasive, mildly corrosive, conducts electricity when wet, and does not dissolve in water.”¹¹¹ Ash accumulation can cause roof collapse or other structural damage.¹¹² Aircraft that encounter the ash cloud can lose engine power, a serious problem for commercial carriers or rescue operations. If the ash contaminates the water supply, it can cause a shortage of potable water for citizens. Ash can also cause “damage at hydroelectric facilities, irrigation pumping stations, sewage-treatment facilities, and storm water systems.”¹¹³ Some of these issues were seen in the 1980 eruption of Mount St. Helens.

As also was demonstrated by the Mount St. Helens eruption, during a natural disaster when water is compromised providing a clean water supply is critical. Volcanic ash contamination of the water supply and the need to ensure water availability in the event of a fire forced the establishment of water rationing systems on communities. The method of rationing varied by area. In the aftermath, an increased demand for water led the city of Ellensburg, Washington, to double its water usage by 2.5 times the average for four days.¹¹⁴ This increased water usage was due to ash clean-up activities. Luckily, supplies of uncontaminated well water were available for some communities downwind

¹⁰⁹ “1980 Cataclysmic Eruption,” U.S. Geological Survey, accessed June 15, 2016, https://volcanoes.usgs.gov/volcanoes/st_helens/st_helens_geo_hist_99.html.

¹¹⁰ “1980 Cataclysmic Eruption,” U.S. Geological Survey.

¹¹¹ “Volcanic Ash,” U.S. Geological Survey, accessed June 15, 2016, https://volcanoes.usgs.gov/volcanic_ash/ash.html.

¹¹² “Buildings,” U.S. Geological Survey, accessed June 15, 2016, https://volcanoes.usgs.gov/volcanic_ash/buildings.html.

¹¹³ Ibid.

¹¹⁴ “Mt. St. Helens 1980,” U.S. Geological Survey, accessed June 15, 2016, https://volcanoes.usgs.gov/volcanic_ash/mount_st_helens_infrastructure.html.

of the eruption, without which the “demand would have exceeded supply to a much greater extent.”¹¹⁵

Wastewater also became an issue due to the ash fall. At the Yakima water treatment plant, “15 times the usual amount of solid matter was being removed” during the pre-treatment stage.¹¹⁶ In the following days, the ash clogged the machinery at the treatment plant and plugged the lines.¹¹⁷ Three days after the eruption, the Yakima city manager issued a press release about a system failure at the Yakima sewage-treatment plant. Damage to the plant ultimately cost approximately \$4 million.¹¹⁸ Local and state officials took steps to ensure that a more cohesive plan for water safety was in place for future eruption incidents.

Transportation is another important area of that was negatively impacted by the ash fall from Mount St. Helens. A number of eastern Washington airports were shut down due to poor visibility and ash accumulation. Thousands of flights were either grounded or re-routed during the two-week shutdown.¹¹⁹ Roadways that were not damaged or destroyed had to be closed “due to visibility and traction issues for vehicles,” and most did not open for another two weeks.¹²⁰ The USGS noted that 185 miles of road were “destroyed or extensively damaged” because of the eruption.¹²¹ In addition, 48 bridges were damaged or destroyed.

The damage to transportation infrastructure was caused by pyroclastic flows, lahars, and ash fall. Pyroclastic flows are a “chaotic mixture of rock fragments, gas, and ash that travels rapidly (ten meters per second) away from the volcanic vent or collapsing flow front”¹²² while lahars are volcanic or debris mudflow. Pyroclastic flows and lahars

¹¹⁵ “Mt. St. Helens 1980” U.S. Geological Survey.

¹¹⁶ Ibid.

¹¹⁷ Ibid.

¹¹⁸ Ibid.

¹¹⁹ “Impact and Aftermath,” U.S. Geological Survey, accessed June 15, 2016, <http://pubs.usgs.gov/gip/msh/impact.html>.

¹²⁰ “Mt. St. Helens 1980,” U.S. Geological Survey.

¹²¹ Ibid.

¹²² “Glossary,” U.S. Geological Survey.

from Mount St. Helens left over 6 feet of debris along roads near Mount St. Helens. However, the most important factor became the removal of the ash.

After the 1980 eruption, electrical circuits and transformers were temporarily damaged by the ash fall. A week later, rainfall hit the area and power shorted out once again due to the combination of the weight of the wet ash causing “insulator flashover.”¹²³ The flashovers caused numerous fires due to the flammable nature of the wooden utility poles. Researchers found that “The Bonneville Power Administration (BPA), which transmits electricity across much of the Pacific Northwest, experienced 25 momentary and 25 sustained outages in the initial 10 days following the eruption.”¹²⁴

Central Washington was not prepared when Mount St. Helens erupted in 1980, much like the United States is ill-prepared for a NEO impact, and the lessons learned from the disastrous eruption could be invaluable for creating a U.S. NEO mitigation strategy. In particular, these lessons focus on the areas of education and training, infrastructure protection, and communications. The location of Mount St. Helens puts it in the jurisdiction of the United States, offering insight into how the various state and local governments assign and share duties. In the case of Mount St. Helens, despite the long lead-up to the eruption, the public was widely uninformed and uneducated about the issue, and emergency personnel were not prepared for the level of interagency cooperation needed to address these issues. Furthermore, the public and government officials were uncertain of the effects of the ash cloud on infrastructure and health, but they learned a great deal in the aftermath of the eruption. The effects of the ash cloud on wildlife, the population, and infrastructure can offer a wealth of knowledge, as a NEO impact would cause a similar debris cloud. Officials also recognized that creating a communications strategy that emphasizes key impacts to citizens can result in more cooperation during a natural disaster. The public needs to be aware of the threat beforehand, which can be accomplished by disseminating information among both civilians and relevant aid groups.

¹²³ “Mt. St. Helens,” U.S. Geological Survey.

¹²⁴ Ibid.

1. Citizen Education and Training

After the 1980 eruption of Mount St. Helens, disaster management officials identified weak areas of response and worked to strengthen a pre-event preparation strategy. The ash fall from Mount St. Helens caused the most concern due to its far-reaching negative impacts. Citizens of the area are now more informed of the risk of a volcanic eruption, and since the incident, the focus has been on education and preparedness. Charles Erwin, emergency management specialist for the city of Yakima, recommends emergency supply kits for residents and stresses the importance of including dust masks and goggles to help in the event of ash fall.¹²⁵ According to Erwin, nearby cities now have plans in place for clearing and disposing of the ash from streets, and “how to answer citizens’ questions about what to do with it.”¹²⁶ This emphasis on taking time to educate and empower is important because it directly involves citizens in the mitigation strategy.

Disaster management training is another important component in improving preparedness and responses during all phases of a disaster.¹²⁷ Before the 1980 eruption, training drills were not a regular event for a volcano response team. This lack of training in 1980 endangered the lives of citizens, isolated response groups because of limited communications, and created confusion about the effects of ash fall. Doug Ficco, a maintenance engineer with the Washington state Department of Transportation, notes that “multi-agency drills are [now] part of the routine,” whereas before the disaster, Washington “didn’t have relationships in place with the Corps of Engineers and the National Guard.”¹²⁸ The eruption revealed the need for training among the various agencies, which ultimately enhanced collaboration and also shed light on potential weaknesses of the mitigation strategy.

¹²⁵ Kate Prengaman, “Planning, Coordination Have Come a Long Way since Eruption of Mount St. Helens,” *Emergency Management*, May 18, 2015, <http://www.emergencymgmt.com/training/Planning-Coordination-Eruption-Mount-St-Helens.html>.

¹²⁶ Ibid.

¹²⁷ “Training in Disaster Management,” International Federation of Red Cross and Red Crescent Societies, accessed September 4, 2016, <http://www.ifrc.org/en/what-we-do/disaster-management/preparing-for-disaster/disaster-preparedness-tools/training-for-response/>.

¹²⁸ Kate Prengaman, “Planning, Coordination Have Come a Long Way.”

Investment in volcano monitoring technology that can help notify and educate the community was another outcome from the 1980 eruption.¹²⁹ The Johnston Ridge Observatory is run by the USGS and now has more robust monitoring and informational capabilities. The observatory's website, a technology unavailable in 1980, is easy to navigate, and it is informative, and regularly updated. Researchers at the observatory closely monitor volcanic activity on the mountain, issue forecasts, disseminate warnings, and spearhead studies to more fully understand the eruptive threat.¹³⁰ Investing in technology to understand and monitor the threat helps create more understanding for first responders, who can then adjust their mitigation plans accordingly. These changes to protocol demonstrate that researchers are now more focused on the hazards of an eruption and on monitoring the threat in real time.

2. Infrastructure Mitigation

Strong infrastructure is necessary for a population to successfully operate, yet it was compromised in the 1980 eruption of Mount St. Helens. Reinforcing and building infrastructure is one of the main priorities for the National Volcano Early Warning System (NVEWS), of which the Cascades Volcano Observatory is a member. NVEWS was created by the USGS after the eruption and “guides strategic, long-term improvements to U.S. volcano monitoring infrastructure and integrated volcano hazard information products and services for a range of users, including emergency managers, land managers, communities, businesses, other Federal and State agencies, and the public.”¹³¹ Including such a wide spectrum of stakeholders allows for these individuals to create better practices and stronger infrastructure in the event of an eruption.

The abundance of ash fall greatly impacted the surrounding communities and their equipment. Maintenance lessons were as simple as covering the external equipment with plastic. Workers also noted that pre-treatment equipment controls would have to be

¹²⁹ Kate Prengaman, “Planning, Coordination Have Come a Long Way.”

¹³⁰ *Volcano Hazards: Exploring the National Preparation and Response Strategy*, U.S. House Committee on Natural Resources, 113th Cong., 2 (2014), 5.

¹³¹ Ibid., 6.

adjusted for “maximum removal rates” to accommodate the excess ash.¹³² Public health officials and citizens would also need to be informed of the potential consequences of ash in the water systems.¹³³ Lastly, collaborative efforts would include contacting equipment manufacturers for assistance in maintaining or repairing equipment.¹³⁴

Ash removal and disposal was an arduous but important task after the eruption. Dump sites were chosen based on proximity due to the urgency of removing the debris.¹³⁵ Some examples of chosen dump sites were quarries or landfills. These areas were then “covered with topsoil and seeded with grass” to minimize the chance that wind would cause the ash to become airborne again.¹³⁶ Ultimately, the cost of ash removal totaled \$2.2 million, and it took Yakima over two months to finish.¹³⁷ The biggest lesson learned for ash removal was to identify disposal sites prior to an eruption and to disseminate that site information to all stakeholders and have “residents, businesses, and utilities coordinate their activities.”¹³⁸

Ash from an eruption can also have negative implications for the power grid. The immediate removal of ash is integral to maintaining the power supply. For example, ash accumulation of .6 inches “can cause flashover on insulators on power lines, resulting in power loss.”¹³⁹ Air blasting can be used to clear dry ash from surfaces, but wet ash can only be successfully removed through high pressure water.¹⁴⁰ Small measures such as providing regular maintenance to equipment can also provide more stability to the power grid in a time of crisis. Consistently clearing ash from trees near power lines is one

¹³² “Mt. St. Helens 1980,” U.S. Geological Survey.

¹³³ Ibid.

¹³⁴ Ibid.

¹³⁵ “Impact and Aftermath,” U.S. Geological Survey.

¹³⁶ Ibid.

¹³⁷ Ibid.

¹³⁸ Ibid.

¹³⁹ *Volcano Hazards*, House Committee on Natural Resources, 5.

¹⁴⁰ “Volcanic Ash: Effects & Mitigation Strategies,” Alaska Volcano Observatory, accessed June 16, 2016, <http://www.avo.alaska.edu/ash/power/>.

measure that can help to keep power outages at a minimum. If power is kept on, people are less likely to panic and responders are better able to continue their mitigation efforts.

3. Communications Lessons Learned

The communications issue extends to disseminating emergency information to the public as well as among relevant agencies and stakeholders when responding to a disaster. In the case of Mount St. Helens, warning and informing the public fell to the State of Washington Department of Emergency Services. The service was “underfunded,” “neglected,” and “directed by an inexperienced political appointee rather than a hazards professional.”¹⁴¹ The department issued a warning to local communities hours after the eruption occurred, and ultimately a federal disaster was declared. FEMA stepped in and issued a series of fact sheets to answer a number of questions for the public. This information could have been more effective if it had been issued in the weeks and months before the eruption, when the USGS first noticed the increased activity on Mount St. Helens.¹⁴²

It is important to tailor communications in a way that encourages the public to understand the threat and take appropriate action, but not panic. The U.S. Forest Service did an admirable job of keeping citizens out of harm’s way using roadblocks, setting up an information office, and “developing a contingency plan for an eruption” and worked massive amounts of overtime trying to keep ahead of the situation, but the public did not understand the threat.¹⁴³ It was only in the aftermath that people started to understand the gravity of the situation when the ash cloud, which many people believed was an approaching storm system, closed roads, stranded cars, and caused health concerns. After the eruption, both civilians and emergency personnel understood the risks associated with a volcanic event more thoroughly, encouraging the warning system, predictions, and public communications to become “more effective.”¹⁴⁴

¹⁴¹ Saarinen, “Warning and Response.”

¹⁴² Ibid.

¹⁴³ Ibid.

¹⁴⁴ Ibid.

B. EYJAFJALLAJÖKULL ERUPTION

On April 14, 2010, Eyjafjallajökull, an Icelandic volcano largely unknown to most of the world, erupted with severe consequences to both Europe and the world. Thanks to advances in telecommunications since the 1980 St. Helens eruption, the impacts of this volcanic eruption were televised to an international audience, 24 hours a day. Eyjafjallajökull was an eye-opening event for the public and governments across Europe.¹⁴⁵

Eyjafjallajökull's initial eruption on March 20, 2010, produced lava on the north-east side of the volcano, and soon after another eruption phase started near the caldera, or volcanic crater, causing the surrounding ice to melt and flood southern Iceland.¹⁴⁶ Researchers found that approximately 25 percent of the 1 cubic kilometer of "ice in the summit crater...melted in the first two days of the eruption." The resulting combination of magma and water caused an ash cloud that reached over 33,000 feet into the atmosphere. The ash cloud, pushed by wind, spread toward the "Faroe Islands, Norway, and northern Scotland."¹⁴⁷ Researchers estimated that the volcano produced eruptions of approximately 750 tons of magma every second, causing most of the crater ice to melt.¹⁴⁸ Activity seemed to decrease by the end of April, but it was not until May 23rd that ash fall decreased to almost nothing.¹⁴⁹

Due to the location of Iceland in the middle of trans-Atlantic flight channels, and the effects of drifting ash on European countries downwind of the volcano, the ash cloud caused the greatest impact to air transportation.¹⁵⁰ During the week of April 15, dozens of countries closed their airports, totaling 300 airport closures, and "a correspondingly large airspace" was also restricted. At one point during the eruption, almost 80 percent of

¹⁴⁵ "Eyjafjallajokull Eruption, Iceland: April/May 2010," British Geological Survey, accessed September 4, 2016, http://www.bgs.ac.uk/research/volcanoes/icelandic_ash.html.

¹⁴⁶ Ibid.

¹⁴⁷ Ibid.

¹⁴⁸ Ibid.

¹⁴⁹ Ibid.

¹⁵⁰ "Aviation," U.S. Geological Survey, accessed June 15, 2016, https://volcanoes.usgs.gov/volcanic_ash/ash_clouds_air_routes_eyjafjallajokull.html.

flights in Europe were canceled due to airport closures.¹⁵¹ According to the USGS, 7 million passengers were affected by the closure, 100,000 flights were cancelled, and \$1.7 billion in airline revenue was lost.¹⁵² The grounded flights and delays almost resulted in medical emergencies for some. As an example, transport of bone marrow from the United States for recipients in Europe was delayed, which caused great concern as bone marrow is only viable for transplant within 72 hours.¹⁵³

During the 2010 eruption, officials were uncertain of what constituted safe ash levels for aircraft, which ultimately caused mass airport closures. In hindsight, a clearer understanding of safe and unsafe ash levels for aviation would have been useful in making airport closure decisions. Instead, decisions were made using a risk-aversive approach versus one based on scientific data.¹⁵⁴ The event offered researchers an opportunity to learn more about ash clouds.

The United Kingdom led the airport closure response after information from the International Airways Volcano Watch (IAVW) was disseminated. Other European countries, from Russia to Italy, emulated the United Kingdom's decision and closed their airports. The intent was to avert risk and ensure the safety of human lives, but "the response was purely reactive."¹⁵⁵ The United Kingdom's 2010 edition of the National Risk Register made no mention of a volcanic ash cloud event, and therefore no real conception of the potential hazards of a "volcanic ash aviation emergency" existed.¹⁵⁶ The UK uses an emergency management system that classifies a crisis into "bronze," "silver," "gold," "diamond," and "platinum."¹⁵⁷ These colors are the signifiers for the level of leadership and strategy necessary to oversee a crisis. The top tiers, "diamond"

¹⁵¹ David. Alexander, "Volcanic Ash in the Atmosphere and Risks for Civil Aviation: A Study in European Crisis Management," *International Journal of Disaster Risk Science* 4, no. 1 (March 2013): 11, doi: 10.1007/s13753-013-0003-0.

¹⁵² "Aviation," U.S. Geological Survey.

¹⁵³ Alexander, "Volcanic Ash in the Atmosphere," 12.

¹⁵⁴ Ibid., 13.

¹⁵⁵ Ibid., 14.

¹⁵⁶ Ibid.

¹⁵⁷ Ibid.

and “platinum,” translate to the involvement of the Prime Minister in the Cabinet Office Briefing Room (COBRA).¹⁵⁸ It was four days before the first COBRA meeting convened, which shows “a lack of visible leadership” when many stakeholders were floundering in the midst of the crisis.¹⁵⁹ Decision makers executed a piecemeal approach that led certain countries to be more decisive and others to simply follow their tenuous lead.¹⁶⁰

The 2010 eruption of Eyjafjallajökull impacted most of Europe, and officials worked to form a mitigation plan in the midst of the crisis, which ultimately left them with a number of lessons learned. The unpredictable nature of the volcano and the ensuing ash cloud caused a large-scale air transportation shutdown in Europe. Officials worked to create a mitigation strategy that focused on the areas of education and training, infrastructure, and communications.

This case study can serve as a model for how best to respond to an event that gives little forewarning and can have significant impact, such as a NEO. More specifically, ash fall and a debris cloud are two major concerns with a NEO event. In addition, studying an international response gives insight especially into how the coordination of numerous states can be improved during a crisis. Knowledge on the dispersion and effects of an ash cloud, such as the one produced by Eyjafjallajökull, has researchers calling for an emphasis on education. No protocols existed at the time of the eruption for an aviation ash cloud event. Furthermore, infrastructure was severely strained because of the ash cloud and resulting airport closures. This meant aviation limits for an ash cloud exposure were unknown during the most critical times. Researchers found that much was lacking in the communications strategy that was employed during the eruption, which resulted in a lack of public understanding of the threat. A great deal of this misunderstanding and inaccurate information stemmed from the lack of coordination between airlines and officials. Also, many of the aid organizations were not active in the social media world, which left a large community

¹⁵⁸ Alexander, “Volcanic Ash in the Atmosphere,” 14.

¹⁵⁹ Ibid.

¹⁶⁰ Ibid.

without the information that only those organizations could provide.¹⁶¹ Application of these lessons could be useful in constructing a comprehensive mitigation strategy for a NEO impact.

1. Domestic Response

Iceland's sparse population, small size, and close proximity to other European countries combined with the widespread impact of the eruption's ash cloud caused the response to be largely international. As previously mentioned, Great Britain took the lead in crisis management due to its "proximity" and the effects of the ash cloud on its territory.¹⁶² However, one of the domestic measures Iceland took was monitoring the volcano. The Icelandic Meteorological Office (IMO) monitors and records activity that may signal danger from an impending eruption. Observations are executed 24 hours a day and staff is on call at all hours.¹⁶³

Approximately 500 locals, mostly farmers, were evacuated due to their close proximity to the volcano. The ash cloud caused poor visibility and the closure of surrounding roadways. Authorities cautioned farmers about ash contamination of the water supply and emphasized the health risks posed to livestock, especially sheep, who drank it. The surrounding international community experienced the greatest threat because of the ash cloud trajectory, which significantly increased the international response.

¹⁶¹ Lee, Preston, and Green, *Preparing for High-Impact, Low-Probability Events*, 24.

¹⁶² Elin Thora Ellertsdotir, "Eyjafjallajokull and the 2010 Closure of European Airspace: Crisis Management, Economic Impact, and Tackling Future Risks," in *The Student Economic Review*, vol. XXVIII, 30, accessed September 4, 2106, https://www.tcd.ie/Economics/assets/pdf/SER/2014/elin_thora.pdf.

¹⁶³ "QA on the Eruption in Eyjafjallajokull 2010," Icelandic Meteorological Office, last modified April 17, 2010, <http://en.vedur.is/earthquakes-and-volcanism/articles/nr/1880>.

2. International Response

The 2010 eruption of Eyjafjallajökull opened the world's eyes to the havoc a volcano could cause in the modern world.¹⁶⁴ Piero Dellino, volcanologist with the University of Bari, commented, "our complex society is not prepared to face natural hazards...we have to therefore learn from this lesson."¹⁶⁵ Prior to the 2010 eruption of Eyjafjallajökull, little had been written about the "organizational, logistical, risk management, and decision-making processes associated with volcanic ash emergencies for aviation."¹⁶⁶ As previously mentioned, the United Kingdom, which took the lead in the crisis, had published a new edition of its National Risk Register in 2010, but offered no protocol for a volcanic ash aviation emergency.¹⁶⁷

The need for technological and scientific advances enables better real-time monitoring of "the content and concentration of fine ash in the eruption cloud."¹⁶⁸ Along those lines, the International Civil Aviation Organization (ICAO) created a global Volcanic Ash Advisory Center (VAAC) in 1986 with the purpose of determining "the locations and movements of ash clouds in the atmosphere."¹⁶⁹ There are nine VAAC centers that receive the bulk of their data from civilian meteorological satellites.¹⁷⁰ The information is then used to create an "atmospheric dispersion model" that will predict cloud trajectories.¹⁷¹ The VAAC then issues advisories called SIGMETs (SIGNificant METeorological information) to "inform airline dispatchers, pilots, and air-traffic managers of hazardous weather-related hazards, including ash clouds."¹⁷² The advisories

¹⁶⁴ Erik Klemetti, "Eyjafjallajökull One Year On: What Have We Learned (and Not Learned)?" *Big Think*, accessed September 4, 2016, <http://bigthink.com/eruptions/eyjafjallajokull-one-year-on-what-have-we-learned-and-not-learned>.

¹⁶⁵ Charles Q. Choi, "Why Iceland Volcano's Eruption Caused So Much Trouble," *Live Science*, February 7, 2012, <http://www.livescience.com/31127-iceland-volcano-ash-plume-trouble.html>.

¹⁶⁶ Alexander, "Volcanic Ash in the Atmosphere," 9.

¹⁶⁷ Ibid., 14.

¹⁶⁸ Choi, "Why Iceland Volcano's Eruption Caused So Much Trouble."

¹⁶⁹ "Aviation," U.S. Geological Survey.

¹⁷⁰ Ibid.

¹⁷¹ Alexander, "Volcanic Ash in the Atmosphere," 14.

¹⁷² "Aviation," U.S. Geological Survey.

are regularly updated “over time periods of minutes to hours” and posted on websites.¹⁷³ These real-time updates can be invaluable when monitoring an ash cloud and ensuring aviation safety. VAAC was instrumental during the Eyjafjallajökull eruption as aviation was largely impacted.

New measures and protocols were created after the Eyjafjallajökull eruption when officials realized their previous strategy did not account for the volatility and unpredictability of nature.¹⁷⁴ After the crisis, a risk regulation expert noted, “EU integration does not yet extend to air traffic management.”¹⁷⁵ The disconnected response strategies across Europe made the task of mitigating the problem and informing the public more difficult.¹⁷⁶

The eruption triggered a new awareness in Europe about the hazards of ash clouds on aviation as well as the need for policy. ICAO met later that year to discuss the aviation issues and establish new policy for aviation volcanic ash events. One of the outcomes from the ICAO meeting was a regional contingency plan in the event of a volcanic ash disruption.¹⁷⁷ The plan provides important information on what ash levels are hazardous as well as when “bulletins” should be issued to “aviation personnel, including pilots.”¹⁷⁸ The intent is to disseminate accurate information quickly and efficiently to those who would be most impacted by the ash.

Another outcome of Eyjafjallajökull’s eruption and the resulting air disaster was the formation of a new group called the International Volcanic Ash Task Force (IVATF). ICAO appointed the group to “examine how best to define hazardous airspace and manage aviation risk.”¹⁷⁹ Members include stakeholders from both the government and private sector who are involved in “regulation, operations, and scientific

¹⁷³ “Aviation,” U.S. Geological Survey.

¹⁷⁴ Alexander, “Volcanic Ash in the Atmosphere,” 9–19.

¹⁷⁵ Ibid., 14.

¹⁷⁶ Ibid.

¹⁷⁷ Ibid.

¹⁷⁸ Ibid.

¹⁷⁹ “Aviation,” U.S. Geological Survey.

investigations.”¹⁸⁰ This partnership, between both public and private sector groups, allows for a more comprehensive plan. The 2010 eruption drastically impacted aviation, so involving all stakeholders in the IVATF is a prudent decision that will foster communication between states, will lead to more decisiveness among leaders, and promote greater understanding before the next event occurs.

Communications play an important role for both public and private sector entities during an event such as Eyjafjallajökull’s eruption. In this case, the number of airspace stakeholders created issues for communicating clearly and comprehensively. Airspace ownership is a complex issue as there are “many organizations and initiatives that have a stake in managing access.”¹⁸¹ After the eruption, various regulating entities were fragmented on the issue of regulating European skies.¹⁸² Because of this disconnectedness, Eurocontrol focused on fast-tracking the Single European Sky initiative. This initiative would “coordinate the management and regulation of airspace across Europe.”¹⁸³ Single European Sky moderates airspace by “functional blocks” rather than by national borders.¹⁸⁴ This system increases efficiency and would result in a “faster coordinated response in a crisis.”¹⁸⁵

Real-time information and reporting is another practice that can be employed for future eruption events. ICAO recommended that the Volcano Observatories use a notification system to alert the aviation sector about volcanic activity. A color coded system was created in response to the recommendation. The system provides information on volcanic activity, whether it is increasing or decreasing, and as of 2013 is used by a

180 “Aviation,” U.S. Geological Survey.

181 Alexander, “Volcanic Ash in the Atmosphere,” 15.

182 Ibid.

183 Ibid.

184 “Single European Sky,” Eurocontrol, accessed September 4, 2016,
<http://www.eurocontrol.int/dossiers/single-european-sky>.

185 James Kanter and Nicola Clark, “European Union Agrees to Accelerate Joint Control of Skies,” *The New York Times*, May 4, 2010, http://www.nytimes.com/2010/05/05/world/europe/05ash.html?_r=1.

number of Volcano Observatories in the “United States, Russian Federation, New Zealand, Iceland, and...Australia.”¹⁸⁶

Communicating risk to the public is another important component that is integral after a HILP event. Effective communications during a crisis foster “credibility and legitimacy, which may determine the effectiveness of actions taken to manage any current crisis and prepare for future ones.”¹⁸⁷ After the eruption, researchers found that giving the public in-depth, scientific knowledge of the event and its risks would have been helpful.¹⁸⁸ Unfortunately, this was not what happened during the 2010 ash cloud event and “scientists, weather forecasters, engineers and other experts need to be given a greater voice in the traditional media.”¹⁸⁹ The effects of this kind of communication can keep the public from panicking, build confidence in the decision-making, and create interest in the issue.¹⁹⁰ In addition, providing solid information keeps people from attempting to find their own online, which can be inaccurate and spread quickly through social media.

Researchers found that during the 2010 eruption, “pre-established internal and external communication plans were essential; and that in future they should be implemented as part of an organization’s overall travel policy and crisis management plans.”¹⁹¹ The growing popularity of social media platforms being used for quick sound bites of news continues, and it only makes sense that officials use every avenue available for disseminating information. Social networks are powerful tools, “a network of networks,” with the ability to reach a greater audience. Research has shown that bloggers are more likely to use information found online through a social network due to the ease of being notified about the story.¹⁹² One key component for a successful communications

¹⁸⁶ “Aviation,” U.S. Geological Survey.

¹⁸⁷ Lee, Preston, and Green, *Preparing for High-Impact, Low-Probability Events*, 23.

¹⁸⁸ Ibid.

¹⁸⁹ Ibid.

¹⁹⁰ Ibid., 24.

¹⁹¹ Ibid.

¹⁹² Lee, Preston, and Green, *Preparing for High-Impact, Low-Probability Events*, 25.

strategy is to establish a social media presence before an event occurs to build public trust. This approach allows the organization to become the “go to” for information during an actual crisis rather than having the conversation dominated by another, less credible source as was the case in 2010 when the travel industry drowned out the more informed voices of scientists and air traffic control.¹⁹³

C. CONCLUSION

Both case studies in this chapter shared some similarities while still offering unique recommendations. For example, both case studies highlight the importance of educating citizens and officials about the event before it happens. The Mount St. Helens case offered practical lessons for securing infrastructure and lifeline services. Eyjafjallajökull’s eruption gave officials insight into the impact volcanic ash fall can have on travel, particularly on air transportation. Both case studies also outlined the need for increased communications between agencies and accurate updates to citizens. However, since the Mount St. Helens eruption occurred well before the social media age, Eyjafjallajökull offered new insight into the role that this media can play during a crisis. These conclusions will help to strengthen the volcano mitigation strategy for each location, and many recommendations could be used for forming a NEO mitigation strategy.

¹⁹³ Lee, Preston, and Green, *Preparing for High-Impact, Low-Probability Events*, 26.

IV. LESSONS FROM EARTHQUAKE CASE STUDIES

This chapter examines two major earthquake events: the case of the 1989 Loma Prieta Earthquake in California will be examined first, followed by the 2011 Great East Japan Earthquake. Both were large impact events that hit populations familiar with this type of threat, but valuable lessons were learned and incorporated into future mitigation strategies. Each case will include a short overview of the eruption, and its effects, followed by lessons learned in the areas of education and training, infrastructure, and communications.

A. LOMA PRIETA EARTHQUAKE

In 1989, San Francisco and the surrounding Bay Area experienced a 6.9 magnitude earthquake that caused mass destruction in a densely populated area.¹⁹⁴ The quake originated at Loma Prieta Peak in the nearby Santa Cruz Mountains, and although lasting only for 15 seconds, was felt as far away as Los Angeles.¹⁹⁵ The Marina district, in San Francisco, experienced the most damage as its buildings had been constructed on filled land. Filled land is land that has been built up from wetlands and along shorelines by filling it in with another material, such as loose rocks; in the case of the Marina district the infill was with “dune sand and building rubble” from the 1906 San Francisco Earthquake.¹⁹⁶ The unstable sand provided poor support for building foundations during the earthquake, causing the structures to collapse;¹⁹⁷ a total of 67 people died and 3,000

¹⁹⁴ “1989 San Francisco Earthquake,” History Channel, accessed September 4, 2016, <http://www.history.com/topics/1989-san-francisco-earthquake>.

¹⁹⁵ *Encyclopaedia Britannica*, s.v. “San Francisco – Oakland Earthquake of 1989,” last modified December 23, 2015, <https://www.britannica.com/event/San-Francisco-Oakland-earthquake-of-1989>; Paul O’Brien and Dennis S. Miletic, “Citizen Participation in Emergency Response Following the Loma Prieta Earthquake,” *International Journal of Mass Emergencies and Disasters* 10, no. 1 (March 1992): 71–89, accessed September 4, 2016, <http://www.ijmed.org/articles/502/download/>.

¹⁹⁶ “Liquefaction Damage in the Marina District from the 1989 Loma Prieta Earthquake” (poster), California Geological Survey, accessed July 15, 2016, <http://www.conservation.ca.gov/cgs/information/outreach/documents/marina%20poster%2011x17rw2b.pdf>

¹⁹⁷ “1989 San Francisco Earthquake,” History Channel.

were injured as a result.¹⁹⁸ The majority of deaths were caused when a 1.25 mile section of the Cypress Street Viaduct collapsed onto its lower level.¹⁹⁹ The earthquake also caused fires due to damaged gas mains.²⁰⁰ The Loma Prieta Earthquake resulted in \$6 billion in damages and was the “most costly natural disaster in the United States” since the 1906 earthquake in San Francisco.²⁰¹

The Loma Prieta Earthquake caused substantial damage to infrastructure including roads, bridges, water mains, and the power grid, which hindered aid efforts. It caused power loss to over 150,000 people and based on the current population, the loss would be close to 500,000.²⁰² Power loss results in the loss of critical services, or “lifelines,” when they are most needed.²⁰³ During the earthquake, the collapse of the Cypress Street Viaduct ultimately resulted in the death of 35 people.²⁰⁴ Before the event, earthquake engineers requested that the City of Oakland update the viaduct according to the latest safety code.²⁰⁵ Officials stated that the collapse could have been avoided if the recommended safety updates had been made.²⁰⁶

Ultimately, the Loma Prieta earthquake caused losses to lifeline infrastructure systems, though a great deal was learned from these impacts. Losses resulted in information that was used to improve the resilience of critical systems, which are essential for any disaster, such as a NEO impact. Preparing for an unpredictable threat, such as an earthquake or a NEO, can limit the loss of life and infrastructure destruction.

198 “1989 San Francisco Earthquake,” History Channel.

199 Ibid.

200 Ibid.

201 O’Brien and Miletí, “Citizen Participation in Emergency Response,” 71–72.

202 David Raths, “7 Ways the Response to a Devastating Earthquake Has Changed,” *Emergency Management*, September 20, 2013, <http://www.emergencymgmt.com/disaster/7-Ways-Response-Loma-Prieta-Earthquake.html?page=2>.

203 Kathleen J. Tierney, *Emergency Preparedness and Response: Lessons from the Loma Prieta Earthquake* (Newark, DE: University of Delaware Disaster Research Center, 1993), 18, <http://udspace.udel.edu/handle/19716/578>.

204 “Cypress Street Viaducts,” *Engineering.com*, October 13, 2006, <http://www.engineering.com/Library/ArticlesPage/tabid/85/ArticleID/73/categoryId/7/Cypress-Street-Viaducts.aspx>.

205 Ibid.

206 Ibid.

1. Education and Training

Citizens of California are accustomed to the threat of earthquakes and receive education as early as grade school on what to do in the event of a quake. This method of educating early and often is especially important so that in a time of crisis, the response is automatic. For example, during the 1989 Loma Prieta Earthquake, “effective training of staff and students in emergency procedures” ensured that no student, teacher, or administrator was seriously injured during the event.²⁰⁷ Earthquake drills are practiced during the school year, and both children and adults memorize “drop, cover, and hold on” as the actions one takes in the midst of a quake.²⁰⁸ After the 1989 earthquake, researchers Linda Bourque and James Goltz studied the citizen response during and after the event. Their survey showed that 75 percent of respondents stopped what they were doing and took cover.²⁰⁹ People who were in familiar places such as at work, school, or home followed the “drop, cover and hold on” protocol, whereas people in public spaces were disoriented and did not perform the safety protocol.²¹⁰ The latter response shows a need for revised training that teaches “how to scan and quickly assess a location for safety” and how to keep individuals from being a danger to themselves or those nearby during a crisis.²¹¹ The Bay Area Urban Areas Security Initiative (UASI) has since increased the frequency of drill and training exercises in the region. For example, in 2011, the UASI spent \$3.3 million on training exercises and increased the annual number of responders trained from 500 to 1200.²¹² These responders hailed from different areas of disaster management such as “emergency management, emergency medical services, firefighting,

²⁰⁷ Michael Newman, “Well-Prepared Schools Mostly Spared in California’s Devastating Earthquake,” *Education Week*, October 25, 1989, <http://www.edweek.org/ew/articles/1989/10/25/09110040.h09.html>.

²⁰⁸ “Earthquake Preparedness and Response,” Occupational Safety and Health Administration (OSHA), accessed September 4, 2016, <https://www.osha.gov/dts/earthquakes/preparedness.html>.

²⁰⁹ Tierney, *Emergency Preparedness and Response*, 4.

²¹⁰ Ibid.

²¹¹ Ibid.

²¹² Raths, “7 Ways the Response to a Devastating Earthquake Has Changed.”

law enforcement, and hazardous materials response,” thereby creating a more educated and versatile response team.²¹³

Today, the FEMA website offers information on earthquake protocol for adults and children. In addition, a massive drill called the “Great California Shakeout” started in 2015 and occurs annually on the anniversary of the 1989 Loma Prieta Earthquake. More than 10 million Californians registered and participated in the first drill.²¹⁴ Linking the drill to the 1989 earthquake makes a connection in the minds of many who experienced the quake firsthand. The effort, which is sponsored by FEMA, USGS, and NSF, also offers drill manuals for various groups such as schools, businesses, non-profit organizations, disabled persons, government agencies, and the healthcare industry.²¹⁵ Emergency disaster response teams were strained during the 1989 earthquake, and practices were later revised. The current earthquake response strategy is very different than the one employed in 1989.²¹⁶ For example, the updated strategy was tested in an annual “Golden Guardian” statewide exercise in 2013.²¹⁷ During the drill, the Department of Emergency Management (DEM) worked closely with FEMA and the U.S. Navy on communicating and coordinating a citywide recovery for a scenario wherein a magnitude 7.8 earthquake hit San Francisco.²¹⁸

2. Infrastructure Mitigation

After the earthquake, officials recognized the importance of reinforcing infrastructures for critical organizations, buildings, and roads. The California Utilities Emergency Association works with utility companies on the interdependencies between

²¹³ Raths, “7 Ways the Response to a Devastating Earthquake Has Changed.”

²¹⁴ Amy Hollyfield and Drew Tuma, “Bay Area Takes Part In Great California Shakeout Drills,” *ABC News*, October 15, 2015, <http://abc7news.com/news/bay-area-takes-part-in-great-california-shakeout-drills/1034307/>.

²¹⁵ “Shakeout Resources,” Southern California Earthquake Center, accessed on September 4, 2016, <http://shakeout.org/resources/>.

²¹⁶ Raths, “7 Ways the Response to a Devastating Earthquake Has Changed.”

²¹⁷ Sarah Rich, “Major Earthquake Scenario Tests California’s Response Capabilities,” *Emergency Management*, May 16, 2013, <http://www.emergencymgmt.com/training/San-Francisco-Holds-Shelter-and-Feeding-Exercises-for-Earthquake-Preparedness.html>.

²¹⁸ Ibid.

systems and on the establishment of protocols to keep systems running, or to get them back online in the event of a disaster.²¹⁹ The association has also worked with utility companies in other California regions to establish mutual assistance agreements in the event of a magnitude 7.0 earthquake.²²⁰ Boland notes, “the type of system we have for pulling resources from elsewhere did not exist during Loma Prieta … the utilities realize they are no longer silos and are working together.”²²¹ By increasing the level of coordinated training among groups, the level of preparedness increases as more resources are available in the event of a crisis.

After the earthquake, the collapsed viaduct was redesigned with the updated safety protocols. The updates involved retrofitting columns with steel plates and using rubber isolators to minimize earthquake vibrations.²²² Experts concluded that the reason the viaduct was so impacted by the earthquake was due to “a lack of knowledge and understanding of the geotechnical area” and a lack of compliance with engineer suggestions for safety upgrades.²²³ Reinforcing infrastructure can greatly reduce the odds of buildings collapsing and limit debris falling on people.

3. Communications Lessons Learned

Since the 1989 earthquake, new communications technology has also become available and been incorporated into the mitigation strategy. For example, the Emergency Operations Center relies on a WebEOC “incident management tool for situational awareness” to further facilitate communication between the disaster management groups, which was a technology unavailable during the 1989 earthquake.²²⁴ This system might have addressed the problem in 1989 when “there were major difficulties with interorganizational communication” as the various agencies were communicating on a

²¹⁹ Raths, “7 Ways the Response to a Devastating Earthquake Has Changed.”

²²⁰ Ibid.

²²¹ Ibid.

²²² “Cypress Street Viaducts,” *Engineering.com*.

²²³ Ibid.

²²⁴ Rich, “Major Earthquake Scenario.”

number of different radio frequencies.²²⁵ Employing a uniform system increases communications among groups and enables the dissemination of accurate information.

In 1991, a law was passed in California that requires a formal “incident command system” during disasters that provides clarity and “facilitate[s] the flow of emergency information and resources within and between the organizational levels.”²²⁶ This structure allows seasoned disaster management officials to make critical decisions, rather than directing them to the mayor.²²⁷ Having a clear protocol during a disaster is imperative for making timely decisions and executing rescue operations.

Since 1989, the USGS has partnered with the American Red Cross and the United Way in creating earthquake hazard messages for citizens and other aid groups. Pamphlets, published in multiple languages, were initially disseminated to 2 million people via the Sunday morning newspaper.²²⁸ Due to their popularity, the pamphlets were reissued in 1994, and over 5 million copies have since been distributed.²²⁹ Officials in other earthquake-prone areas have created their own information bulletins and modeled them after the USGS version.

The USGS also routinely provides earthquake information to news stations to ensure that accurate messages are aired. This media outreach is particularly important as one of the findings from the 1989 earthquake was that the media portrayed the event as being worse than it was by initially inflating fatalities and only showing the massive destruction of the Marina district. First responders in surrounding areas were misled by these media reports, which resulted in them not requesting aid and resources from nearby

²²⁵ Tierney, *Emergency Preparedness and Response*, 18.

²²⁵ Ibid.

²²⁶ Raths, “7 Ways the Response to a Devastating Earthquake Has Changed.”

²²⁷ Ibid.

²²⁸ Thomas M. Brocher et al., *Progress toward a Safer Future since the 1989 Loma Prieta Earthquake* (Fact Sheet 2014-3092) (Reston, VA: U.S. Geological Survey, 2014), doi: 10.3133/fs20143092.

²²⁹ Ibid.

communities.²³⁰ Ensuring accurate disaster information is important to both first responders and citizens during a crisis.

Social media has become an increasingly popular resource for officials and the public during a crisis, but it was not available during the 1989 earthquake. Today, the San Francisco DEM has established a social media presence across various platforms and is working to incorporate it into a response strategy. For example, now San Francisco uses Twitter to publish warnings and status updates. AlertSF, a text-based notification system for San Franciscans, also sends emergency alerts to area residents on events ranging from traffic accidents to “citywide post-disaster information.”²³¹

B. GREAT EAST JAPAN EARTHQUAKE

On March 11, 2011, a 9.0 earthquake shook the seafloor of the Pacific Ocean for six minutes, sending tsunami waves as high as 128 feet to strike Tokohu, Japan, and leaving a lasting impact on citizens.²³² The earthquake was the strongest ever recorded to hit Japan, causing the deaths of thousands and culminating in a mega disaster due to a nuclear meltdown.²³³ The Great East Japan Earthquake was more than just an earthquake; it was an “earthquake, a tsunami, a nuclear power plant accident, a power supply failure, and a large-scale disruption of supply chains.”²³⁴

The initial earthquake caused the seafloor to shift upward by 30 feet in a section that is larger than the state of Connecticut.²³⁵ This shift was the catalyst for the tsunami that decimated much of the Tohoku coastline. The tsunami’s impact included the deaths of 20,000 people, the destruction of 130,000 houses, and the shutdown of public

²³⁰ Tierney, *Emergency Preparedness and Response*, 16.

²³¹ Raths, “7 Ways the Response to a Devastating Earthquake Has Changed.”

²³² Becky Oskin, “Japan Earthquake & Tsunami of 2011: Facts and Information,” *Live Science*, May 7, 2015, <http://www.livescience.com/39110-japan-2011-earthquake-tsunami-facts.html>.

²³³ Karl Tate, “How Japan’s 2011 Earthquake Happened (Infographic),” *Live Science*, March 10, 2013, <http://www.livescience.com/27773-how-japan-s-2011-earthquake-happened-infographic.html>.

²³⁴ Frederica Ranghieri and Mikio Ishiwatari, eds., *Learning from Megadisasters: Lessons from the Great East Japan Earthquake* (Washington, DC: World Bank, 2014), 2, doi: 10.1596/978-1-4648-0153-2.

²³⁵ Tate, “How Japan’s 2011 Earthquake Happened.”

transportation and roadways.²³⁶ Fukushima, Iwate, and Miyagi suffered the most damage.

In Japan's recorded history, the population had not seen an event of this magnitude with such a high impact and low probability of occurrence.²³⁷ Nevertheless, according to an after-action report, Japan's advanced disaster management response “proved its worth … the loss of life and property could have been far greater if the country's policies and practices had been less effective.”²³⁸ Prior to the 2011 earthquake, Japan had invested heavily in disaster management mitigation features to improve policies, infrastructure, building regulations, and decision-making processes, which lessened the impact of the earthquake.²³⁹

The Japanese government takes a comprehensive approach to disaster risk management, and a key element is its emphasis on training and education for both citizens and officials of various agencies. Local governments are staffed with well-trained and well-educated disaster responders.²⁴⁰ For example, Japan's “central government encourages local governments to promote structural measures by providing financial support, producing technical guidelines and manuals, and conducting training for technical staff in planning, design, operation, and maintenance.”²⁴¹

One specific pre-hazard measure used to foster education and training drills was the dissemination of hazard maps. For reference, hazard maps detail information on evacuation routes, shelter locations, and high-risk areas.²⁴² The hazard maps that were distributed during the 2011 event included important information that saved lives. However, Japanese officials learned that only 20 percent of households in the area most

²³⁶ Ranghieri and Ishiwatari, *Learning from Megadisasters*, 2.

²³⁷ Ibid.

²³⁸ Ibid., 3.

²³⁹ Ibid., 5.

²⁴⁰ S. Fraser et al., *Tsunami Evacuation: Lessons from the Great East Japan Earthquake and Tsunami of March 11th 2011*, (Lower Hutt, New Zealand: GNS Science, 2012), 7, <http://crew.org/sites/default/files/SR%202012-017.pdf>.

²⁴¹ Ranghieri and Ishiwatari, *Learning from Megadisasters*, 6.

²⁴² Fraser et al., *Tsunami Evacuation*, 14–15.

impacted had received the maps, which shows that the number of recipients needs to increase substantially.

Before the 2011 earthquake, Japan had created a robust infrastructure to guard against natural hazards. Some of the mitigation measures taken included an extensive levee system, strict building codes, and seismically sensitive public trains.²⁴³ While the levees did not withstand the 2011 tsunami, the structures allowed some citizens a few more minutes to evacuate to higher ground.²⁴⁴ A breakwater built at Kamaishi Bay, which was ultimately destroyed, was able to weaken the tsunami by approximately 40 percent.²⁴⁵ An important takeaway for officials was the potential size a tsunami could reach, as levees and breakwaters that may have been sufficient for average tsunamis were insufficient for the 2011 tsunami.

The 2011 event resulted in a number of issues for “fixed-line” and mobile-phone infrastructure. For example, the exchange facility was inundated by water from the tsunami, which caused “damage to underground cables and conduits, destruction of telephone poles and overhead cables, destruction and loss of mobile-phone base stations, and draining of backup batteries during the long power outages.”²⁴⁶ To facilitate communications for people to either confirm the safety of themselves or their loved ones, telecommunications carriers organized an emergency messaging network.²⁴⁷

Japan’s tsunami warning system is the most sophisticated in the world, but the system was still unprepared for the magnitude of the tsunami. It is comprised of satellite communications and “hundreds of real-time monitoring stations” and despite that technology, underestimated the size of the approaching tsunami.²⁴⁸ The Japan Meteorological Agency (JMA) monitors seismic activity, and in 2011, a warning was disseminated to disaster management officials in the first few minutes after the

²⁴³ Ranghieri and Ishiwatari, *Learning from Megadisasters*, 9.

²⁴⁴ Fraser et al., *Tsunami Evacuation*, 36.

²⁴⁵ Ibid.

²⁴⁶ Ranghieri and Ishiwatari, *Learning from Megadisasters*, 133.

²⁴⁷ Ibid., 135.

²⁴⁸ Ibid., 91.

earthquake.²⁴⁹ Initial estimates placed the tsunami's height at three to six meters, which was well below the actual figure. Revisions to the estimate were made, but ultimately, approximately 70 percent of the population did not receive the updated information.

The early warning systems are often what most encourage people to evacuate to safer zones. Research shows that approximately 60 percent of people who heard the early earthquake warnings took action, such as evacuating or seeking shelter.²⁵⁰ To further complicate matters, many of the radio networks suffered equipment damage that put broadcasts out of commission and prohibited disaster management officials from using the radio as a means of communicating important information to tsunami victims.

Overall, Japan's strategy for applying the lessons learned from previous earthquakes and tsunamis ensured that the country was more prepared than most for a large-scale disaster such as the 2011 earthquake and subsequent tsunami. Employing a similar advanced preparation strategy could also be beneficial in forming a NEO mitigation strategy, specifically in the areas of education and training, infrastructure, and communications. Japan could offer insight into how the public can be involved in the pre-event planning stages by receiving education on the hazards and by practicing training drills. In addition, buildings that had been reinforced to meet the strict safety codes were able to withstand the earthquake. Japanese officials also learned the importance of communicating accurate warnings to the public and aid groups as they may be the only updates received during the disaster. Similarly, a NEO impact could happen quickly, disrupting communications, and there may be limited time to issue warnings.

1. Domestic Response

Japanese leaders continuously work to fortify and modify their disaster risk management system. Japan emphasizes the importance of community participation for a successful mitigation strategy, a factor that contributed to countless lives saved during the 2011 event.²⁵¹ Citizens are aware of the dangers of natural disasters that have historically

²⁴⁹ Ranghieri and Ishiwatari, *Learning from Megadisasters*, 92.

²⁵⁰ Ibid., 96.

²⁵¹ Ibid., 6.

hit Japan, and “community based disaster risk management activities are well integrated into the daily lives of most Japanese.”²⁵² Parents communicate the hazards of tsunamis to children through stories.²⁵³ Training drills are also emphasized and, in 2010, Japan conducted a national earthquake drill in which 670,000 people participated.²⁵⁴ Local neighborhood groups, known as Jichikai, are involved in decision-making meetings and assigned roles in the event of a disaster.²⁵⁵

Volunteers from these community groups were some of the first responders.²⁵⁶ Locals had also participated in evacuation drills prior to the event, which ultimately saved many lives.²⁵⁷ Researchers found that “most people saved from major disasters are rescued by relatives within the first 24 hours—before professional responders can get there,” demonstrating the importance of encouraging and promoting community involvement through pre-disaster training drills. This organized participation was an asset to Japan and reinforced the need for communities to “explore and identify [their] best defense, mixing various soft and hard measures, policies, investments, education initiatives, and drills through sound analysis and stakeholder consultations.”²⁵⁸

Buildings that met Japan’s most current building codes were able to withstand the event with only some damage.²⁵⁹ Japan is frequently subjected to earthquakes, which prompted the government and academics to conduct research on building damage and to update building code regulations.²⁶⁰ The infrastructure reinforcement meant that most of the buildings survived the initial earthquake, but could not withstand the ensuing

²⁵² Ranghieri and Ishiwatari, *Learning from Megadisasters*, 6.

²⁵³ Fraser et al., *Tsunami Evacuation*, 25.

²⁵⁴ James Jay Carafano, *The Great Eastern Japan Earthquake: Assessing Disaster Response and Lessons for the United States* (SR-94) (Washington, DC: Heritage Foundation, 2011), 4, http://thf_media.s3.amazonaws.com/2011/pdf/sr0094.pdf.

²⁵⁵ Ranghieri and Ishiwatari, *Learning from Megadisasters*, 6.

²⁵⁶ Ibid., 6, 67.

²⁵⁷ Fraser et al., *Tsunami Evacuation*, 13.

²⁵⁸ Ranghieri and Ishiwatari, *Learning from Megadisasters*, 6.

²⁵⁹ Ibid., 9.

²⁶⁰ Ibid., 33.

tsunami.²⁶¹ Japan's building codes are stringent and consistently evolve, as more is understood about natural hazards and the damage they can cause.

The roads and highways were also used as disaster management facilities or temporary shelters due to the fact that they had been designed to withstand impacts from an earthquake or tsunami.²⁶² In addition, Japan had equipped its bullet trains with earthquake sensors that would stop the train as soon as earthquake activity occurred.²⁶³ This function allowed all trains to safely stop after the 2011 earthquake, preventing further loss of life.²⁶⁴

The catastrophic damage to the Fukushima Daiichi nuclear power station by the tsunami became one of the largest lessons learned for Japan. Although the power station had protective measures installed in the event of a natural hazard, the sheer enormity of the 2011 event led to massive failure of those safety measures. An after-action report found that one of the points of failure was that "complex scenarios with multiple hazards consisting of earthquakes and tsunamis, compounded by simultaneous transport and communications failures, had not been foreseen."²⁶⁵ This finding could be applied to a NEO strategy, as a NEO impact would also involve multiple hazards and mitigation strategies.

Communications systems are integral during all stages of an event to perform such tasks as disseminating warnings, keeping emergency personnel informed, and confirming the safety of loved ones. Ensuring good communications for the accurate dissemination of information "enables individuals and communities not only to stay safe, but also to contribute more effectively to relief and recovery."²⁶⁶ Officials learned that earthquake warning technology would need to be continually refined, but also, "no matter

²⁶¹ Ranghieri and Ishiwatari, *Learning from Megadisasters*, 35; Fraser et al., *Tsunami Evacuation*, 37–38.

²⁶² Ranghieri and Ishiwatari, *Learning from Megadisasters*, 52.

²⁶³ Ibid., 96.

²⁶⁴ Ibid.

²⁶⁵ Ibid., 10.

²⁶⁶ Ibid., 7.

how advanced technology becomes," citizens should evacuate for higher ground when an earthquake hits."²⁶⁷

Additionally, the use of social media in disaster management has been expanding, and social media played a critical role in the 2011 event. Researchers found that Twitter, in particular, was the most used social media platform for people to relay information during the disaster.²⁶⁸ Twitter published a blog that detailed how best to use the service in a disaster and identified specific hashtags relevant to the event, using both English and Japanese to communicate with a larger audience. The company also created a site that was accessible via mobile phone without the Twitter application.²⁶⁹ Publishing this site allowed access to 115 million phone users in Japan.²⁷⁰ The Japanese population at the time of the disaster was approximately 126 million, which means that 91 percent of the population would have been able to access the Twitter site.²⁷¹

Facebook is one of the most popular social media platforms in the world and was also used during the 2011 disaster in several different ways.²⁷² The network allowed people to contact loved ones and receive updates on the conditions in Japan. Aid organizations and volunteers created Facebook groups "to help with the relief efforts in terms of direct support and informational support ... [and] it provided the means of communication for the groups to function."²⁷³ After-action reports and the media labeled Facebook "a lifeline in the disaster."²⁷⁴ Another way Facebook assisted communication efforts was to create a main page, called 'Disaster Relief' with relevant disaster information.²⁷⁵ This page also placed relevant information on blackouts and

²⁶⁷ Ranghieri and Ishiwatari, *Learning from Megadisasters*, 96.

²⁶⁸ Brett D. M. Peary, Rajib Shaw, and Yukiko Takeuchi, "Utilization of Social Media in the East Japan Earthquake and Tsunami and its Effectiveness," *Journal of Natural Disaster Science* 34, no. 1 (2012): 7, accessed September 5, 2016, http://www.jsnds.org/jnds/34_1_1.pdf.

²⁶⁹ Ibid.

²⁷⁰ Ibid.

²⁷¹ Ibid.

²⁷² Ibid.

²⁷³ Ibid.

²⁷⁴ Ibid.

²⁷⁵ Ibid., 8.

transportation schedules onto users' Newsfeeds, meaning that users would see the messages first when logging in.²⁷⁶ Also, while many of the inundated phone lines were out of service, mobile phone users could access the website due to cellular broadband capabilities.²⁷⁷

2. International Response

After the earthquake, the United States stepped in to offer immediate assistance to the Japanese people. One of the main priorities was ensuring that funding was made available to assist in the rescue of citizens. The United States Agency for International Development (USAID) took over coordination of response donations and issued \$100k immediately after the U.S. Ambassador declared the Japanese earthquake an emergency.²⁷⁸ In addition, on March 12, 2011, the Secretary of Defense directed \$35 million in Overseas Humanitarian, Disaster, and Civic Aid (OHDACA) to Japan.²⁷⁹

The United States also sent an experienced disaster management team from Washington, DC, to Japan. This group of experts, including those from the Department of Energy and the Department of Health and Human Services, was created to research and mitigate the after-effects of the earthquake, namely the nuclear radiation spill. Subject matter experts also worked closely with the Japanese government in monitoring the "path of any radioactive release."²⁸⁰

Before Operation Tomodachi, a disaster relief operation comprised of U.S. military, U.S. military branches that were already stationed in, or near, Japan facilitated operations such as search and rescue, translation assistance, and medical support.²⁸¹ This

²⁷⁶ Peary, Shaw, and Takeuchi, "Utilization of Social Media," 8.

²⁷⁷ Ibid.

²⁷⁸ Macon Phillips, March 13, 2011 (6:52 p.m.), "The Ongoing Response to the Earthquakes and Tsunami in Japan," *The White House Blog*, accessed September 4, 2016, <https://www.whitehouse.gov/blog/2011/03/13/ongoing-response-earthquakes-and-tsunami-japan>.

²⁷⁹ Andrew Feickert and Emma Chanlett-Avery, *Japan 2011 Earthquake: U.S. Department of Defense (DOD) Response* (CRS Report No. R41690) (Washington, DC: Congressional Research Service, 2011), 1, <https://www.fas.org/sgp/crs/row/R41690.pdf>.

²⁸⁰ Macon Phillips, "The Ongoing Response," *The White House Blog*.

²⁸¹ Feickert and Chanlett-Avery, *Japan 2011 Earthquake*, 1.

large military presence was integral for allowing immediate support to the Japanese after the earthquake. U.S. government officials worked with their Japanese counterparts during the event and offered extensive military resources.²⁸² Operation Tomodachi employed 16 naval ships to assist with the disaster relief and response efforts after the earthquake.²⁸³ This immediate coordination and knowledge sharing improved the response in Japan and protected the international community by tracking the spread of the nuclear spill.

C. CONCLUSION

California and Japan are both earthquake-prone areas with disaster management officials who focus on educating the public on the disaster before it happens, which increases the likelihood of an effective response. This process of continuously updating the public could be valuable for creating a disaster management strategy for other largely unpredictable events, such as a NEO. Additionally, incorporating pre-event training exercises for officials and citizens can limit the loss of life during an actual crisis. Loma Prieta and the Great East Japan Earthquake caused losses to lifeline infrastructure systems ranging from transportation to the power grid, but a great deal was learned because of those impacts. Furthermore, Japan's robust infrastructure offers examples of how to shore up roads, transportation, and critical services. Both the Loma Prieta Earthquake and the Great East Japan Earthquake highlighted the need for communication between disaster groups and for dissemination of accurate information to the public. These events, much like a NEO, are unavoidable and unpredictable, but with proper planning the consequences do not have to be catastrophic.

²⁸² Alexander Kaczur, Jayson Aurelio, and Edelio Joloya, "An Analysis of United States Naval Participation in Operation Tomodachi Humanitarian and Disaster Relief in the Tsunami-Stricken Japanese Mainland" (MBA professional report, Naval Postgraduate School, 2012), 7, http://calhoun.nps.edu/bitstream/handle/10945/7366/12Jun_Kaczur_Joloya_Aurelio_MBA.pdf?sequence=1&isAllowed=y.

²⁸³ Ibid., 8.

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V. CONCLUSION AND RECOMMENDATIONS

The previous case study chapters have highlighted areas of disaster management and response that have been the most effective. These measures are not a guarantee against loss of life or damage to infrastructure, but they have greatly lessened the degree of impact from natural disasters. This chapter will state the lessons that can best be applied to a NEO impact event and provide recommendations on a way forward.

Education and training should focus on both first responders and the general public. First responders need to receive education on NEOs to plan exercises and scenarios that would provide the most suitable preparedness training for an impact. The public also needs to be educated on the NEO threat and how they should respond in the event of an impact event. The Japanese disseminated hazard maps to identify important information and a similar tactic could be used for public education of NEOs. Patrick Lynett, assistant professor of civil engineering at Texas A&M, researched the after-effects of tsunamis and “noted that the disaster reinforces the importance of education in preparing the public to respond to such events.”²⁸⁴ As discussed in Chapter IV, when the Japanese earthquake occurred there was insufficient warning and little time for locals to escape the tsunami. The public had to respond based on knowledge from previous training. Similarly, a NEO impact could strike with little or no advance warning, requiring the public to be educated on matters such as shelter locations or evacuation routes.

The eruptions of Mount St. Helens and Eyjafjallajökull resulted in increased research into the threat of volcanic eruptions and prompted the modification of disaster protocols. These new protocols are particularly relevant to a NEO impact because of what was learned about the effects of ash and volcanic debris on important areas of infrastructure. Researchers collected data on the movement of ash clouds and, in the case of Eyjafjallajökull, saw firsthand that ash could shut down the airline industry. The

²⁸⁴ Patricia Jones Kershaw and Byron Mason, *The Indian Ocean Tsunami Disaster: Implications for U.S. and Global Disaster Reduction and Preparedness* (Washington, DC: National Academies Press, 2006), 2, doi:10.17226/11619.

experience gained on the effects of ash on airplane engines gave emergency personnel a better idea of what the machines can withstand before airborne ash reaches unsafe levels. This information is critical as responders likely will need to rely on aircraft to conduct rescue and transport operations for those affected by a NEO event. Additionally, the establishment of new policy on safe levels of ash for aviation can be used in a NEO crisis.

As learned from the Loma Prieta and Great East Japan earthquakes, reinforced disaster-resistant structures are often a critical component to mitigation practices for other HILP events. Russell Schweickart, co-founder of the Association of Space Explorers and the B612 Foundation, asserts that evacuation is an “important element of mitigation, for it is by far the most likely case we are facing. But it requires further development of infrastructure.”²⁸⁵ Research suggests that a NEO impact with little to no advance warning is a likely scenario and, in these cases, government officials would need to ensure that potential shelters, such as schools or churches, meet required safety standards.

An organized communications strategy is another component of HILP event responses. Richard Eisner, coastal regional administrator for the California Office of Emergency Services (OES), “stressed the importance of reliable warning systems and the need to provide accurate information to the general public.”²⁸⁶ Conveying accurate information to other agencies and the public could limit the loss of life. These agencies need to relay this information to disaster response teams as they are attempting rescues, and members of the public need to be kept informed as they seek safety. The case studies examined in this thesis offer both traditional and newer methods to promote communications among citizens and disaster management officials. Ultimately, the costs of implementing education and exercise planning, infrastructure development, and communications may be significantly less than those of the large-scale mitigation projects that involve action from space.

²⁸⁵ Clark R. Chapman and Russell L. Schweickart, “NEO Mitigation and Coordination with the Disaster Management Community” (paper presented at 1st IAA Planetary Defense Conference: Protecting Earth from Asteroids, Granada, Spain, April 27–30, 2009).

²⁸⁶ Kershaw and Mason, *The Indian Ocean Tsunami Disaster*, 5.

A. DOMESTIC RECOMMENDATIONS

The importance of before-hand disaster training and preparedness as highlighted in previous chapters would be integral to a NEO impact strategy. The first step is to educate people on the NEO threat. The only exposure many have had to the idea of a NEO impact is through film or television. Accurate information, based on scientific research, needs to be made available to the general public well in advance. An effective start could be adding NEO awareness education to school curricula so that people learn about the threat from an early age. In addition, the potential after-effects of a NEO impact, such as shattered windows from a shockwave or a debris cloud, should be outlined so the public knows what to expect. The intent is not to cause fear or panic, but to limit the amount that is unknown to the public and responders.

Participating in training exercises has been shown to limit the loss of life and improve disaster response strategies. The U.S. government should partner with NASA on creating a protocol for a NEO event similar to the drop, cover, and hold on protocol that is practiced during earthquakes. In the 1950s and 1960s, “duck and cover” and sheltering drills were practiced regularly in schools.²⁸⁷ In this case, it may be a combination of taking cover and also seeking shelter elsewhere. In the event of an impact, there would likely be mass confusion, and preventative measures such as pre-training drills could lead to a more organized response.

Strong infrastructure offers protection in a disaster and ensures critical operations can continue, making it an important component of disaster management. One of the big concerns of a NEO event is having buildings that can withstand the effects of an impact or shockwave. Reinforcements can include small measures such as shatter-safe glass. Larger measures might be constructing a structure that could be used as a NEO-resistant shelter. For the latter, which involves engineering capabilities and new technology, it could be useful to propose an infrastructure challenge similar to the Google Lunar X-Prize challenge.

²⁸⁷ Linton Weeks, “Living in the Atomic Age: Remember These Images?” *NPR, South Carolina Public Radio*, March 17, 2011, <http://www.npr.org/sections/pictureshow/2011/03/17/134604352/images-of-the-atomic-age>.

In 2007, Google launched a competition for teams to create a rover that could land on the moon, “travel 500 meters, and transmit back high definition video and images.”²⁸⁸ These teams are privately funded and upon completion of a successful project receive award money from a \$30 million prize fund. This initiative crowdsourced ideas from outside the government and incentivized the process. To date, a handful of teams have reached milestones toward the final goal, but the process is still ongoing. A similar competition could be used to create NEO-resistant structures or habitats. Additionally, funding for these kinds of projects could be gained by partnering with forward-thinking billionaires. This crowdsourcing of funding occurred recently when Yuri Milner—a Russian billionaire, physicist, and venture capitalist—launched the \$100 million project “Breakthrough Listen” with the purpose of finding extraterrestrial life.²⁸⁹ Milner partnered with two other well-known entrepreneurs: Sergey Brin, Google co-founder, and Mark Zuckerberg, Facebook founder. This method of obtaining funding for these infrastructure projects sidesteps government issues such as bureaucratic delays and lack of funding, but would require a considerable financial contribution without an immediate return on investment.

Media platforms offer both officials and the public the accurate and timely communications they need during a HILP event. Communications for both officials and the public have to be accurate, timely, and available on various media platforms. The integration and increased use of social media in disaster management has been discussed in the previous chapters and should be applied to the NEO issue. For example, establishing a social media presence before the event is helpful in establishing trust and familiarity for people. It is also another method that information on the threat can be presented at all stages: pre-event, during, and after. Facebook and Twitter could be integral aids in a NEO mitigation strategy. In addition to supplying real-time information on an event, they both could offer a platform to convey information on shelters, evacuation, and status updates. In 2014, Facebook introduced a new feature called

²⁸⁸ “Lunar X-Prize Guidelines,” Google, accessed August 20, 2016. <http://lunar.xprize.org/about/overview>.

²⁸⁹ “#73 Yuri Milner,” Forbes, accessed September 4, 2016, <http://www.forbes.com/profile/yuri-milner/>.

“Safety Check” that allows people in disaster areas to digitally check in, so family and friends know they are safe. It was informally used before the official launch during the 2011 Japan earthquake and was more recently employed for the first time in the United States after a gunman opened fire at a Florida nightclub.²⁹⁰ A similar alert, safety check, and informational page could be used in a NEO impact event.

Another communications strategy that could be used to educate the public involves a NEO-centric television program hosted by a well-respected researcher and public figure, such as Neil deGrasse Tyson. In 2014, “Cosmos: A Space Odyssey” premiered on the National Geographic and Fox channels and was an international success. The short series was viewed by 135 million viewers worldwide, of whom 45 million were in the United States.²⁹¹ This number demonstrates both the international interest in space and the expansive impact television can have as a communications tool. The program could also be web-streamed to increase viewership. Using this platform to inform the public about NEOs allows for greater outreach and could generate greater interest in the topic.

B. INTERNATIONAL RECOMMENDATIONS

Ensuring the international community is involved in the NEO mitigation process is in the best interests of the United States for a number of reasons. Expanding the involvement of scientists and researchers across the globe could increase the likelihood of successful NEO strategies. Additionally, making the NEO issue a more prominent global focus would increase resources and funding substantially. Also, the involvement of prominent leaders would help establish legitimacy, resulting in greater public awareness. Since a NEO is a threat to humankind and politically neutral, the list of allies would likely expand. In the event of a NEO impact, increased collaboration and reliance on allies could be critical for saving lives.

²⁹⁰ Stephanie Mlot, “Facebook Safety Check Activated for First Time in US,” *PC Magazine*, June 13, 2016, <http://www.pcmag.com/news/345199/facebook-safety-check-activated-for-first-time-in-us>.

²⁹¹ Rick Kissell, “‘Cosmos’ Draws Biggest Global Audience Ever for National Geographic Channel,” *Variety*, July 7, 2014, <http://variety.com/2014/tv/news/cosmos-draws-biggest-global-audience-ever-for-national-geographic-channel-1201257111/>.

It could be beneficial for the United States to host a summit and take the lead in creating a plan for NEOs. This summit should include international leaders. It is also important to invite representatives from the scientific community who have researched NEOs and can inform attendees on the realities of a NEO impact. Lastly, by including private sector figureheads such as the CEOs of Twitter, Facebook, and SpaceX, a new and more holistic approach to NEOs can be taken. Details on aid, technology sharing, and other assistance can be decided before a NEO event takes place. In addition, this forum could serve as an educational opportunity for other countries without NEO programs. Earth-based and space-based mitigation scenarios could be constructed based on a number of inputs from the community, further strengthening the plan and fostering collaboration between countries.

The European community, much like the United States, also has the opportunity to examine and assess infrastructure resilience for a NEO impact. Other countries could follow the competition initiative to crowd-source ideas for stronger, NEO resistant infrastructure as an Earth-based response, or engineer a deflection device for a space-based mitigation response. Additionally, the international community could partner with the United States to create a challenge that is truly an international initiative to engineer more resilient and robust infrastructure. This would increase the knowledge base, incorporate more players, and ultimately produce more ideas. During the NEO summit, the United States could propose a collaborative infrastructure project similar to the challenge proposed in the domestic recommendations section, but on the international level. Similarly, the international competition could request inputs for the creation of a space-based deflection system. The increase in scope and international participation would allow for increased funding and cost sharing.

Increasing communications and collaboration between countries could also serve to strengthen a NEO response strategy. These communication efforts should be led by prominent figureheads and leaders in each country. Such leaders would have more influence on their people, and their participation would demonstrate an investment in tackling the NEO issue. Ideally, these figureheads would attend the proposed NEO summit and work with their counterparts to create uniform NEO response policies and

protocols. This information would then be translated into different languages and disseminated to citizens through social media sites, during leadership speeches, and on radio and television programs.

Lastly, as no NEO early warning system currently exists, it is critical that a timely early-warning network is established. As demonstrated in the 2011 Japan earthquake, the tsunami warning system offered valuable minutes for citizens to seek shelter. NEOs can also be unpredictable and strike with little warning, as was the case in Chelyabinsk, so it is imperative that a warning network is created to disseminate warnings to citizens and officials. This system could employ both space- and ground-based sensors to aid in the monitoring capabilities.²⁹²

C. LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORK

It must be noted that this thesis and its findings take an in-depth look at only one facet of the NEO impact issue, resulting in some limitations. For example, the potential mass of a NEO could negate a number of recommendations in this study. If the NEO were on scale with the K-T meteor, most Earth-based mitigation options proposed would not be useful. In addition, proposed space-based mitigation efforts might have priority, and the focus may be on detecting objects far in advance. At the time this thesis was written, NASA has agreed to move forward with the next stage of the Asteroid Redirect Mission (ARM), a space-based NEO deflection initiative with an estimated \$1.4 billion cost.²⁹³

These recommendations are only first steps. In the future, researchers could advance the work on NEO impact mitigation in a few different ways. For example, after the international summit, it would be important to test the proposed ideas and set milestones for each stage of implementation. A comparative analysis could be conducted to assess if one competition had stronger results and pinpoint why. The strongest points of each could be highlighted and incorporated into a revised competition.

²⁹² E-mail from co-advisor, Dr. Clay Moltz, 9.1.16.

²⁹³ Ted Ransosa, “NASA Clears Asteroid Redirect Mission Despite \$150 Million Cost Increase,” *Tech Times*, August 17, 2016, <http://www.techtimes.com/articles/174052/20160817/nasa-clears-asteroid-redirect-mission-despite-150-million-cost-increase.htm>.

The after-effects of the media communications strategy could also be evaluated to ascertain if the efforts were successful. One way to do this would be to use Google Analytics, which analyzes website traffic, locations, and queries.²⁹⁴ The location information could be particularly revealing as it would provide insight into where the communications strategy is working. Researchers could also partner directly with Google and receive data on whether web searches related to NEOs were increasing, decreasing, or unchanged. Similarly, Twitter could be used as a resource to pull data on the frequency and trends of NEO-related hashtags. Many bemoan the increasing use of social media, but it can be one of the strongest tools for assessing public interest and awareness of a topic. Much could be done to address the possibility of NEO impacts, and rather than continuing to dismiss the idea of black swans, we must accept their existence and work to address the potential problems they pose.

²⁹⁴ Brad Booth, “Google Analytics: 4 New Reports for SEO,” *Practical Ecommerce*, August 7, 2016, <http://www.practicalecommerce.com/articles/125829-Google-Analytics-4-New-Reports-for-SEO>.

LIST OF REFERENCES

- Alaska Volcano Observatory. “Volcanic Ash: Effects & Mitigation Strategies.” Accessed June 16, 2016. <http://www.avo.alaska.edu/ash/power/>
- Alexander, David. “Volcanic Ash in the Atmosphere and Risks for Civil Aviation: A Study in European Crisis Management.” *International Journal of Disaster Risk Science* 4, no. 1 (March 2013): 9–19. doi: 10.1007/s13753-013-0003-0.
- Bailey, Nicholas J., Graham G. Swinerd, Hugh G. Lewis, and Richard Crowther. “Global Vulnerability to Near-Earth Object Impact.” *Risk Management* 12, no. 1 (February 2010): 31–53. doi:10.1057/rm.2009.16.
- Booth, Brad. “Google Analytics: 4 New Reports for SEO.” *Practical Ecommerce*, August 7, 2016. <http://www.practicalecommerce.com/articles/125829-Google-Analytics-4-New-Reports-for-SEO>.
- British Geological Survey. “Eyjafjallajokull Eruption, Iceland: April/May 2010.” Accessed September 4, 2016. http://www.bgs.ac.uk/research/volcanoes/icelandic_ash.html.
- Brocher, Thomas. M., Robert A. Page, Peter H. Stauffer, and James W. Hendley II. *Progress toward a Safer Future since the 1989 Loma Prieta Earthquake* (Fact Sheet 2014-3092) Reston, VA: U.S. Geological Survey, 2014. doi: 10.3133/fs20143092.
- Carafano, James Jay. *The Great Eastern Japan Earthquake: Assessing Disaster Response and Lessons for the United States* (SR-94). Washington, DC: Heritage Foundation, 2011. http://thf_media.s3.amazonaws.com/2011/pdf/sr0094.pdf.
- Chapman, Clark R., and David Morrison. “Impacts on the Earth by Asteroids and Comets: Assessing the Hazard.” *Nature* 367 (January 1994): 33–40. doi: 10.1038/367033a0.
- Chapman, Clark R., and Russell L. Schweickart. “NEO Mitigation and Coordination with the Disaster Management Community.” Paper presented at 1st IAA Planetary Defense Conference: Protecting Earth from Asteroids, Granada, Spain, April 27–30, 2009.
- Charania, A. C., and Agnieszka Lukaszczuk. “Assessment of Recent NEO Response Strategies for the United Nations.” *AIP Conference Proceedings* 1103, no. 393 (February 2009): 1–9. Accessed September 4, 2016. <http://swfound.org/media/10045/neoresponse-al-iac-2009.pdf>.

- Choi, Charles Q. "Why Iceland Volcano's Eruption Caused So Much Trouble." *Live Science*, February 7, 2012. <http://www.livescience.com/31127-iceland-volcano-ash-plume-trouble.html>.
- Chyba, Christopher F., Paul J. Thomas, and Kevin J. Zahnle. "The 1908 Tunguska Explosion: Atmospheric Disruption of a Stony Asteroid," *Nature* 361 (January 1993), 43, doi: 10.1038/361040a0.
- "Cypress Street Viaducts." *Engineering.com*, October 13, 2006.
<http://www.engineering.com/Library/ArticlesPage/tabid/85/ArticleID/73/categoryId/7/Cypress-Street-Viaducts.aspx>.
- David, Leonard. "Dealing with Asteroid Threats: UN Completes First Planning Phase." *Space*, March 6, 2015. <http://www.space.com/28755-dangerous-asteroids-united-nations-team.html>.
- Dearborn, David S. P., and Jim M. Ferguson. "When an Impactor Is Not Enough: The Realistic Nuclear Option for Standoff Deflection." Paper presented at the 4th IAA Planetary Defense Conference–PDC 2015, Rome, Italy, April 13–17, 2015.
- Directorate of Strategic Planning, United States Air Force. *AF/A8XC Natural Impact Hazard (Asteroid Strike) Interagency Deliberate Planning Exercise After Action Report*. Washington, DC: United States Air Force Headquarters, December 2008. http://neo.jpl.nasa.gov/neo/Natural_Impact_After_Action_Report.pdf.
- Dunham, D. W., H. J. Reitsema, E. Lu, R. Arentz, R. Linfield, C. Chapman, R. Farquhar, A. A. Ledkov, N. A. Eismont, and E. Chumachenko. "A Concept for Providing Warning of Earth Impacts by Small Asteroids." *Solar System Research* 47, no. 4 (2013): 315–324. doi: 10.1134/s0038094613040096.
- Ellertsdottir, Elin Thora. "Eyjafjallajokull and the 2010 Closure of European Airspace: Crisis Management, Economic Impact, and Tackling Future Risks." In *The Student Economic Review*, vol. XXVIII. Accessed September 4, 2016.
https://www.tcd.ie/Economics/assets/pdf/SER/2014/elin_thora.pdf.
- Emel'yanenko, V. V., and B. M. Shustov. "Near-Earth Space Hazards and Their Detection." *Physics-Uspekhi* 56, no. 8 (2013): 833–842. doi: 10.3367/UFNe.0183.201308g.0885.
- Eurocontrol. "Single European Sky." Accessed September 4, 2016.
<http://www.eurocontrol.int/dossiers/single-european-sky>.
- European Space Agency. "Near Earth Objects - NEO Segment." Accessed September 4, 2016.
http://www.esa.int/Our_Activities/Operations/Space_Situational_Awareness/Near_Earth_Objects_-_NEO_Segment.

Feickert, Andrew, and Emma Chanlett-Avery. *Japan 2011 Earthquake: U.S. Department of Defense (DOD) Response* (CRS Report No. R41690). Washington, DC: Congressional Research Service, 2011.
<https://www.fas.org/sgp/crs/row/R41690.pdf>.

Forbes. "#73, Yuri Milner." Accessed September 4, 2016.
[http://www.forbes.com/profile/yuri-milner/.](http://www.forbes.com/profile/yuri-milner/)

Fraser, S., I. Matsuo, G. S. Leonard, and H. Murakami. *Tsunami Evacuation: Lessons from the Great East Japan Earthquake and Tsunami of March 11th 2011*. Lower Hutt, New Zealand: GNS Science, 2012.
<http://crew.org/sites/default/files/SR%202012-017.pdf>.

Gehrels, Tom. "NEO Search Programs - Past, Present, and Future." Space Programs and Technologies Conference, SPACE Conferences and Exposition.
<http://dx.doi.org.libproxy.nps.edu/10.2514/6.1996-4382>.

History Channel. "1989 San Francisco Earthquake." Accessed September 4, 2016.
<http://www.history.com/topics/1989-san-francisco-earthquake>.

Hogenboom, Melissa. "In Siberia in 1908 a Huge Explosion Came out of Nowhere." BBC, July 7, 2016. www.bbc.com/earth/story/20160706-in-siberia-in-1908-a-huge-explosion-came-out-of-nowhere.

Hollyfield, Amy, and Drew Tuma. "Bay Area Takes Part In Great California Shakeout Drills." ABC News, October 15, 2015. <http://abc7news.com/news/bay-area-takes-part-in-great-california-shakeout-drills/1034307/>.

Howell, Elizabeth. "Chelyabinsk Meteor: A Wake-up Call for Earth." Space.com, August 2, 2016. <http://www.space.com/33623-chelyabinsk-meteor-wake-up-call-for-earth.html>.

Icelandic Meteorological Office. "QA on the Eruption in Eyjafjallajokull 2010." Last modified April 17, 2010. <http://en.vedur.is/earthquakes-and-volcanism/articles/nr/1880>.

International Federation of Red Cross and Red Crescent Societies. "Training in Disaster Management." Accessed September 4, 2016. <http://www.ifrc.org/en/what-we-do/disaster-management/preparing-for-disaster/disaster-preparedness-tools/training-for-response/>.

Johnson, Lindley. "United States Government Policy and Approach Regarding Planetary Defense." Near-Earth Object Program. May 29, 2012.
http://neo.jpl.nasa.gov/neo/2011_AG5_LN_intro_wksp.pdf.

- . “NEO Program 2015 for SBAG #12.” Near-Earth Object Program. January 6, 2015.
http://www.lpi.usra.edu/sbag/meetings/jan2015/presentations/SBAG_NEO_Program_Johnson.pdf.
- . “Planetary Defense Coordination Office.” NASA. May 20, 2016.
<https://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/9.25C%20Lindley%20Johnson.pdf>.
- Johnston, Casey. “NASA Asteroid-tracking Program Stalled Due to Lack of Funds.” *Ars Technica*, August 13, 2009, <http://arstechnica.com/science/2009/08/nasa-asteroid-tracking-program-stalled-due-to-lack-of-funds/>.
- Kaczur, Alexander, Jayson Aurelio, and Edelio Joloya, “An Analysis of United States Naval Participation in Operation Tomodachi Humanitarian and Disaster Relief in the Tsunami-Stricken Japanese Mainland.” MBA professional report, Naval Postgraduate School, 2012.
http://calhoun.nps.edu/bitstream/handle/10945/7366/12Jun_Kaczur_Joloya_Aurelio_MBA.pdf?sequence=1&isAllowed=y.
- Kanter, James, and Nicola Clark. “European Union Agrees to Accelerate Joint Control of Skies.” *The New York Times*, May 4, 2010.
http://www.nytimes.com/2010/05/05/world/europe/05ash.html?_r=1.
- Kershaw, Patricia Jones, and Byron Mason, *The Indian Ocean Tsunami Disaster: Implications for U.S. and Global Disaster Reduction and Preparedness*. Washington, DC: National Academies Press, 2006. doi: 10.17226//11619.
- Kissell, Rick. “‘Cosmos’ Draws Biggest Global Audience Ever for National Geographic Channel.” *Variety*, July 7, 2014. <http://variety.com/2014/tv/news/cosmos-draws-biggest-global-audience-ever-for-national-geographic-channel-1201257111/>.
- Klemetti, Erik. “Eyjafjallajökull One Year On: What Have We Learned (and Not Learned)?” *Big Think*. Accessed September 4, 2016.
<http://bigthink.com/eruptions/eyjafjallajokull-one-year-on-what-have-we-learned-and-not-learned>.
- Lee, Bernice, Felix Preston, and Gemma Green. *Preparing for High-Impact, Low Probability Events: Lessons from Eyjafjallajökull*. London, United Kingdom: Chatham House, 2012. Accessed April 5, 2016.
<https://www.chathamhouse.org/publications/papers/view/181179>.
- Ma, Yuehua, Haibin Zhao, and Dazhi Yao. “NEO Search Telescope in China.” *Proceedings of the International Astronomical Union* 2, no. 236 (2006): 381–384. doi: 10.1017/s1743921307003468.

- Maynard, James. "Reliving the Mount St. Helens Eruption of 1980." *Tech Times*, May 8, 2016. <http://www.techtimes.com/articles/156871/20160508/reliving-the-mount-st-helens-eruption-of-1980.htm>.
- Mlot, Stephanie. "Facebook Safety Check Activated for First Time in US." *PC Magazine*, June 13, 2016. <http://www.pc当地.com/news/345199/facebook-safety-check-activated-for-first-time-in-us>.
- National Aeronautics and Space Administration (NASA). "Near Earth Object Program: Frequently Asked Questions." Accessed September 4, 2016. <http://neo.jpl.nasa.gov/faq/>.
- . "K-T Event." Accessed September 4, 2016. <http://www2.jpl.nasa.gov/sl9/back3.html>.
- . "The Tunguska Impact - 100 Years Later." Accessed July 9, 2016. http://science.nasa.gov/science-news/science-at-nasa/2008/30jun_tunguska/.
- . "Planetary Defense Frequently Asked Questions." Accessed July 7, 2016. <https://www.nasa.gov/planetarydefense/faq>.
- . "Planetary Defense Coordination Office." Accessed September 4, 2016. <https://www.nasa.gov/planetarydefense/overview>.
- Newman, Michael. "Well-Prepared Schools Mostly Spared in California's Devastating Earthquake." *Education Week*, October 25, 1989. <http://www.edweek.org/ew/articles/1989/10/25/09110040.h09.html>.
- O'Brien, Paul, and Dennis S. Mileti. "Citizen Participation in Emergency Response Following the Loma Prieta Earthquake." *International Journal of Mass Emergencies and Disasters* 10, no. 1(March 1992): 71–89. Accessed September 4, 2016. <http://www.ijmed.org/articles/502/download/>.
- Occupation Safety and Health Administration (OSHA). "Earthquake Preparedness and Response." Accessed September 4, 2016. <https://www.osha.gov/dts/earthquakes/preparedness.html>.
- Oskin, Becky. "Japan Earthquake & Tsunami of 2011: Facts and Information." *Live Science*, May 7, 2015. <http://www.livescience.com/39110-japan-2011-earthquake-tsunami-facts.html>.
- Peary, Brett D. M., Rajib Shaw, and Yukiko Takeuchi. "Utilization of Social Media in the East Japan Earthquake and Tsunami and its Effectiveness." *Journal of Natural Disaster Science* 34, no. 1 (2012): 3–18. Accessed September 5, 2016. http://www.jsnds.org/jnds/34_1_1.pdf.

Peter, Nicolas, Andrew Barton, Douglas Robinson, and Jean Marc Salotti. "Charting Response Options for Threatening Near-Earth Objects." *Acta Astronautica* 55 (August 2004): 325–334. doi: 10.1016/j.actaastro.2004.05.031.

Planetary Impact Emergency Response Working Group. "Planetary Impact Emergency Response Working Group (PIERWG) Charter." Accessed September 4, 2016. http://www.nasa.gov/sites/default/files/atoms/files/signed_pierwg_charter_10212015.pdf.

Prengaman, Kate. "Planning, Coordination Have Come a Long Way since Eruption of Mount St. Helens." *Emergency Management*, May 18, 2015. <http://www.emergencymgmt.com/training/Planning-Coordination-Eruption-Mount-St-Helens.html>.

Ranghieri, Frederica, and Mikio Ishiwatari, eds. *Learning from Megadisasters: Lessons from the Great East Japan Earthquake*. Washington, DC: World Bank, 2014. doi: 10.1596/978-1-4648-0153-2.

Ranosa, Ted. "NASA Clears Asteroid Redirect Mission Despite \$150 Million Cost Increase." *Tech Times*, August 17, 2016. <http://www.techtimes.com/articles/174052/20160817/nasa-clears-asteroid-redirect-mission-despite-150-million-cost-increase.htm>.

Raths, David. "7 Ways the Response to a Devastating Earthquake has Changed." *Emergency Management*, September 20, 2013. <http://www.emergencymgmt.com/disaster/7-Ways-Response-Loma-Prieta-Earthquake.html?page=2>.

Rich, Sarah. "Major Earthquake Scenario Tests California's Response Capabilities." *Emergency Management*, May 16, 2013. <http://www.emergencymgmt.com/training/San-Francisco-Holds-Shelter-and-Feeding-Exercises-for-Earthquake-Preparedness.html>.

Saarinen, Thomas F. "Warning and Response to the Mount St. Helens Eruption." United Nations Office for Disaster Risk Reduction. Accessed September 4, 2016. <http://eird.org/esp/cdcapra/pdf/eng/doc13413/doc13413-contenido.pdf>.

San Diego State University (SDSU) Geology Department. "How Volcanoes Work." Accessed September 4, 2016. http://www.geology.sdsu.edu/how_volcanoes_work/Stlens.html.

———. "Mt. St. Helens Eruption." Accessed June 15, 2016. http://www.geology.sdsu.edu/how_volcanoes_work/Stlens.html.

Schweickart, Russell L. "Decision Program on Asteroid Threat Mitigation." *Acta Astronautica* 65, no. 9 (2009): 1402–1408. doi: 10.1016/j.actaastro.2009.03.069.

- Schweickart, Russell L., Thomas D. Jones, Frans von der Dunk, and Sergio Camacho-Lara. "Asteroid Threats: A Call for Global Response." Association of Space Explorers. September 25, 2008. <http://www.space-explorers.org/ATACGR.pdf>.
- Smithsonian National Museum of Natural History. "Dinosaurs – Why Did They Go Extinct?" Accessed April 4, 2016.
http://paleobiology.si.edu/dinosaurs/info/everything/why_7.html.
- Southern California Earthquake Center. "Shakeout Resources." Accessed on September 4, 2016. <http://shakeout.org/resources/>.
- Taleb, Nassim Nicholas. "The Black Swan: The Impact of the Highly Improbable." *The New York Times*, April 22, 2007. Accessed June 2, 2016.
http://www.nytimes.com/2007/04/22/books/chapters/0422-1st-tale.html?_r=1.
- Tate, Karl. "How Japan's 2011 Earthquake Happened (Infographic)." *Live Science*, March 10, 2013. <http://www.livescience.com/27773-how-japan-s-2011-earthquake-happened-infographic.html>.
- Tierney, Kathleen J. *Emergency Preparedness and Response: Lessons from the Loma Prieta Earthquake*. Newark, DE: University of Delaware Disaster Research Center, 1993. <http://udspace.udel.edu/handle/19716/578>.
- United Nations Office for Outer Space Affairs. "Recommendations of the Action Team on Near-Earth Objects for an International Response to the Near-Earth Object Impact Threat." Accessed April 4, 2016.
http://www.unoosa.org/oosa/oosadoc/data/documents/2013/aac.105c.11/aac.105c.11.329_0.html.
- . "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies." Accessed April 4, 2016.
<http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.htm>.
- United States Department of State. "Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and under Water." Accessed May 11, 2016.
<http://www.state.gov/t/isn/4797.htm>.
- United States Geological Survey. "1980 Cataclysmic Eruption." Accessed June 15, 2016.
https://volcanoes.usgs.gov/volcanoes/st_helens/st_helens_geo_hist_99.html.
- . "Glossary." Accessed September 5, 2016.
<https://volcanoes.usgs.gov/vsc/glossary/>.
- . "Volcanic Ash Impacts & Mitigation." Accessed June 15, 2016.
https://volcanoes.usgs.gov/volcanic_ash/ash.html.

- . “Aviation.” Accessed June 15, 2016.
https://volcanoes.usgs.gov/volcanic_ash/ash_clouds_air_routes_eyjafjallajokull.html.
- . “Buildings.” Accessed June 15, 2016.
https://volcanoes.usgs.gov/volcanic_ash/buildings.html.
- . “Volcanic Ash.” Accessed June 15, 2016.
https://volcanoes.usgs.gov/volcanic_ash/ash.html.
- . “Why Study Volcanoes?” Accessed June 15, 2016.
https://volcanoes.usgs.gov/observatories/cvo/cascade_volcanoes.html.
- . “Impact and Aftermath.” Accessed June 15, 2016.
<http://pubs.usgs.gov/gip/msh/impact.html>.
- . “Mt. St. Helens 1980,” Accessed June 15, 2016.
https://volcanoes.usgs.gov/volcanic_ash/mount_st_helens_infrastructure.html.
- Vasilyev, N. S. “The Tunguska Meteorite Problem Today.” *Planetary and Space Science* 46, no. 2–3 (1998). Accessed September 4, 2016.
<http://cecelia.physics.indiana.edu/life/meteorite/tunguska.html>.
- Yeomans, D. K., S. Bhaskaran, S. B. Broschart, S. R. Chesley, P. W. Chodas, T. H. Sweetser, and R. Schweickart. “Deflecting a Hazardous Near-Earth Object.” Paper presented at the 1st IAA Planetary Defense Conference—Protecting Earth from Asteroids, Granada, Spain, April 27–30, 2009.

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